FUNDACIÓN AQUAE

TESIS

Exploring strategic farming choices to respond to mitigation and adaptation to climate change

Berta Sánchez Fernández

Madrid 2015

Departando de Economía y Ciencias Sociales Aagrarias
Escuela Técnica Superior de Ingenieros Agrónomos
Universidad Politécnica de Madrid

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Tesis Doctoral

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Madrid 2015

Tribunal nombrado por el Sr. Rector Magfco. de la Universidad Politécnica de Madrid, el día ……… de …………………. de 201…

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Calificación ………………………………………….

EL PRESIDENTE LOS VOCALES

EL SECRETARIO

A Narciso y a mis padres José Manuel y Sabina

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Summary

Alterations in the climatic system due to increased atmospheric concentrations of greenhouse gas emissions (GHG) are expected to have important implications for agriculture, the environment and society. Agriculture is an important source of GHG emissions (12 % of global anthropogenic GHG), but it is also part of the solution to mitigate emissions and to adapt to climate change. Responses to face the challenge of climate change should place agricultural adaptation and mitigation strategies at the heart of the climate change agenda. Agriculture is crucial for the conservation and sustainable use of natural resources, which already stand under pressure due to climate change impacts, increased population, pollution and fragmented and uncoordinated climate policy strategies. The concept of climate smart agriculture has emerged to encompass all these issues as a whole.

When assessing choices aimed at reducing threats to agriculture and the environment under climate change, two research questions arise:

- What information defines smart farming choices?
- What drives the implementation of smart farming choices?

This Thesis aims to provide information on these broad questions in order to support climate policy development focusing in some Mediterranean agricultural systems.

This Thesis integrates methods and tools to evaluate potential farming and policy choices to respond to mitigation and adaptation to climate change. The assessment involves both quantitative and qualitative approaches and integrates agronomic, climate and socioeconomic variables at local and regional scale. The assessment includes the collection of data on previous experimental evidence, and the integration of farmer behaviour and policy choices (e.g., technology, agricultural management and climate policy). The case study areas -- the Doñana coastal wetland (S Spain) and the Aragón region (NE Spain) – illustrate two representative Mediterranean regions where the intensive use of agriculture and the semi-arid conditions are already a concern. Thus the adoption of mitigation and adaptation measures can play a significant role for reaching a balance among equity, economic security and the environment under climate change scenarios.

The multidisciplinary methodology of this Thesis includes a wide range of approaches for collecting and analysing data. The data collection process include revision of existing experimental evidence, public databases and the contribution of primary data gathering by semi-structured interviews with relevant stakeholders (i.e., public administrations, policy makers, agricultural advisors, scientist and farmers among others) and surveys given to farmers. The analytical methods include meta-analysis, water availability models (WAAPA model), decision making analysis (MCA, multi-criteria analysis), statistical approaches (Logistic and Poisson regression models) and science-base policy tools (MACC, marginal abatement cost curves and SOC abatement wedges). The meta-analysis identifies the critical temperature thresholds which impact on the growth and development of three major crops (i.e., rice, maize and wheat). The WAAPA model assesses the effect of climate change for agricultural water management under different policy choices and climate scenarios. The multi-criteria analysis evaluates the feasibility of mitigation farming practices under two climate scenarios according to the expert views. The statistical approaches analyses the drivers and the barriers for the adoption of mitigation farming practices. The science-base policy tools illustrate the mitigation potential and cost effectiveness of the farming practices.

Overall, the results of this Thesis provide information to adapt to, and mitigate of, climate change at farm level to support the development of a comprehensive climate policy and to assist farmers. The findings show the key temperature thresholds and response to extreme temperature effects for rice, maize and wheat, so such responses can be included into crop impact and adaptation models. A portfolio of flexible adaptation and mitigation choices at local scale are identified. The results also provide a better understanding of the stakeholders oppose or support to adopt the choices which could be used to incorporate in local adaptation plans and mitigation regional policy. The findings include estimations for the farming and policy choices on the capacity to improve water supply reliability, abatement potential and cost-effective in Mediterranean regions.

Resumen

Las alteraciones del sistema climático debido al aumento de concentraciones de gases de efecto invernadero (GEI) en la atmósfera, tendrán implicaciones importantes para la agricultura, el medio ambiente y la sociedad. La agricultura es una fuente importante de emisiones de gases de efecto invernadero (globalmente contribuye al 12% del total de GEI), y al mismo tiempo puede ser parte de la solución para mitigar las emisiones y adaptarse al cambio climático. Las acciones frente al desafío del cambio climático deben priorizar estrategias de adaptación y mitigación en la agricultura dentro de la agenda para el desarrollo de políticas. La agricultura es por tanto crucial para la conservación y el uso sostenible de los recursos naturales, que ya están sometidos a impactos del cambio climático, al mismo tiempo que debe suministrar alimentos para una población creciente. Por tanto, es necesaria una coordinación entre las actuales estrategias de política climática y agrícola. El concepto de agricultura climáticamente inteligente ha surgido para integrar todos estos servicios de la producción agraria.

Al evaluar opciones para reducir las amenazas del cambio climático para la agricultura y el medio ambiente, surgen dos preguntas de investigación:

- ¿Qué información es necesaria para definir prácticas agrarias inteligentes?
- ¿Qué factores influyen en la implementación de las prácticas agrarias inteligentes?

Esta Tesis trata de proporcionar información relevante sobre estas cuestiones generales con el fin de apoyar el desarrollo de la política climática. Se centra en sistemas agrícolas Mediterráneos.

Esta Tesis integra diferentes métodos y herramientas para evaluar las alternativas de gestión agrícola y políticas con potencial para responder a las necesidades de mitigación y adaptación al cambio climático. La investigación incluye enfoques cuantitativos y cualitativos e integra variables agronómicas, de clima y socioeconómicas a escala local y regional. La investigación aporta una recopilación de datos sobre evidencia experimental existente, y un estudio integrado sobre el comportamiento de los agricultores y las posibles alternativas de cambio (por ejemplo, la tecnología, la gestión agrícola y la política climática). Los casos de estudio de esta Tesis - el humedal de

Doñana (S España) y la región de Aragón (NE España) - permiten ilustrar dos sistemas Mediterráneos representativos, donde el uso intensivo de la agricultura y las condiciones semiáridas son ya una preocupación. Por este motivo, la adopción de estrategias de mitigación y adaptación puede desempeñar un papel muy importante a la hora de encontrar un equilibrio entre la equidad, la seguridad económica y el medio ambiente en los escenarios de cambio climático.

La metodología multidisciplinar de esta tesis incluye una amplia gama de enfoques y métodos para la recopilación y el análisis de datos. La toma de datos se apoya en la revisión bibliográfica de evidencia experimental, bases de datos públicas nacionales e internacionales y datos primarios recopilados mediante entrevistas semi-estructuradas con los grupos de interés (administraciones públicas, responsables políticos, asesores agrícolas, científicos y agricultores) y encuestas con agricultores. Los métodos de análisis incluyen: meta-análisis, modelos de gestión de recursos hídricos (modelo WAAPA), análisis multicriterio para la toma de decisiones, métodos estadísticos (modelos de regresión logística y de Poisson) y herramientas para el desarrollo de políticas basadas en la ciencia. El meta-análisis identifica los umbrales críticos de temperatura que repercuten en el crecimiento y el desarrollo de los tres cultivos principales para la seguridad alimentaria (arroz, maíz y trigo). El modelo WAAPA evalúa el efecto del cambio climático en la gestión del agua para la agricultura de acuerdo a diferentes alternativas políticas y escenarios climáticos. El análisis multicriterio evalúa la viabilidad de las prácticas agrícolas de mitigación en dos escenarios climáticos de acuerdo a la percepción de diferentes expertos. Los métodos estadísticos analizan los determinantes y las barreras para la adopción de prácticas agrícolas de mitigación. Las herramientas para el desarrollo de políticas basadas en la ciencia muestran el potencial y el coste para reducir GEI mediante las prácticas agrícolas.

En general, los resultados de esta Tesis proporcionan información sobre la adaptación y la mitigación del cambio climático a nivel de explotación para desarrollar una política climática más integrada y ayudar a los agricultores en la toma de decisiones. Los resultados muestran las temperaturas umbral y la respuesta del arroz, el maíz y el trigo a temperaturas extremas, siendo estos valores de gran utilidad para futuros estudios de impacto y adaptación. Los resultados obtenidos también aportan una serie de estrategias flexibles para la adaptación y la mitigación a escala local, proporcionando a su vez una mejor comprensión sobre las barreras y los incentivos para su adopción. La capacidad de mejorar la disponibilidad de agua y el potencial y el coste de reducción de GEI se han estimado para estas estrategias en los casos de estudio. Estos resultados podrían ayudar en el desarrollo de planes locales de adaptación y políticas regionales de mitigación, especialmente en las regiones Mediterráneas.

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List of Abbreviations

AFOLU: Agriculture, Forestry, and Other Land Use

CAP: Common Agricultural Policy

CEIGRAM: Research Centre for the Management of Agricultural and Environmental Risk

CSIC: Consejo Superior de Investigaciones Científicas

EC: European Commission

ECPs: Extended Concentration Pathways

EU: European Union

FAO: Food and Agriculture Organization of the United Nations

GCMs: Global climate models

GDP: Gross domestic product

GHG: Greenhouse gases

IPCC: Intergovernmental Panel on Climate Change

MACC: Marginal Abatement Cost Curve

MAGRAMA: Spanish Ministry of Agriculture, Food and Environment

MCA: Multi-criteria analysis

MPWW: Maximum Potential Water Withdrawal

NASs: National Adaptation Strategies

RCPs: Representative concentration pathways

SOC: Soil organic carbon

SSPs: Shared Socioeconomic Pathways

TAPAS: Agro-Environmental Technology for Sustainable Agriculture

UNFCCC: United Nations Framework Convention on Climate Change

UPM: Technical University of Madrid

WAAPA: Water Availability and Adaptation Policy Analysis

1. Research context and objectives

1.1 Research context

This research was completed within the context of the EU SmartSOIL project and the WWF Adaptation in Doñana project. In these two research projects, the UPM team was coordinated by Professor Ana Iglesias. The research was undertaken from 2011 to 2015 at the Department of Agricultural Economics and Social Sciences in the School of Agricultural Engineering and at the Research Centre for the Management of Agricultural and Environmental Risks (CEIGRAM), both of the Technical University of Madrid (UPM). The Thesis was developed within the Doctoral Degree of Agro-Environmental Technology for Sustainable Agriculture (TAPAS).

SmartSOIL (Sustainable farm Management Aimed at Reducing Threats to SOILs under climate change) is a project of European Union´s Seventh Framework Programme for research, technological development and demonstration (Project number: 289694; 2011-2015, http://smartsoil.eu/). SmartSOIL aims to identify and encourage mitigation and adaptation options that result in an optimized balance between crop productivity, restoration and maintenance of vital soil functions. SmartSOIL evaluates the cost-effectiveness of alternative policy and management choices for different European regions and farming systems under current and future climate. SmartSOIL engages key stakeholders in case study regions and the wider EU in the development of the scientific results, guidelines and policy recommendations and tools.

In this project, the UPM team developed a database of experimental data from previous studies to be used to improve existing soil and crop simulation models. UPM team also developed different social and economic approaches to assess suitable mitigation and adaptation farming and policy choices in a study area of the Mediterranean. This project supported this Thesis by funding and providing the knowledge base for its development. It enabled the field work for the stakeholders' involvement (experts, policy makers, agricultural advisors and farmers) and included interviews, questionnaires and workshops. It was carried out in collaboration with the Senior Researcher Jorge Álvaro-Fuentes of the Aula Dei - Consejo Superior de Investigaciones Científicas (EEAD-CSIC), who is co-supervisor of this Thesis.

The WWF Adaptation in Doñana project (Study of vulnerability to climate change for rice fields in Doñana) also supported and funded this research. This project was funded by the Spanish Biodiversity Foundation of the Spanish Government and implemented by the World Wide Fund for Nature (WWF). UPM was the research coordinator of the project. The WWF Adaptation in Doñana project aims to evaluate climate change vulnerability and identify flexible adaptation options for the rice farming and the biodiversity in the Doñana Protected Area (southern Spain). The UPM team provided a detailed study on the vulnerability and adaptive capacity of the system. The UPM team also provided a portfolio of adaptation farming and policy choices. A participatory process was carried out during the project development to inform and be informed by local stakeholders in the area (public administrations, policy makers and advisors, NGOs, experts and farmers among others). The participatory process during the project included interviews and workshops.

The research supported by the two projects included qualitative and quantitative analysis and extensive fieldwork in the rural areas of Mediterranean. It has yielded four academic papers (three as first author and one as coauthor) and two factsheets for sustainable management, which constitute my Thesis dissertation

In addition to my research experience, in 2012 I spent two months as a visiting scholar at the Department of Plant and Environmental Sciences in the Faculty of Life Sciences, University of Copenhagen, hosted by Professor John R. Porter. During my stay, I had the opportunity to learn about the main features of crop science and climate change and to meet other colleagues working on climate change issues from several countries. This stay was funded by the SmartSOIL project.

1.2 Problem description

Increased human-made atmospheric gases are causing alterations in the climatic systems, and the warming of the climate system is unequivocal (IPCC 2013). In 2010, the total anthropogenic GHG emissions reached 49 (±4.5) $GtCO_2eq/yr$ from all the economic sectors (i.e., energy supply, agriculture, forestry, and other land use, industry, transport and buildings) and 12% (5.0-5.8 $GtCO_2eq/yr$) of total GHG emissions were released from the agriculture (IPCC 2014b).

Changes to the global climate due to increased atmospheric concentrations of GHG are expected to have important implications for crop production, agriculture and socio-economic development (Parry et al. 2004; Lobell and Field 2007; Stern 2007; Iglesias et al. 2011a; Alcamo and Olesen 2012). Both plant growth and development are affected by extreme temperature (Stone, 2001; Barnabás et al. 2008). Severe drought and changes in rainfall will affect the water availability for crop production, particularly in regions where water scarcity is already a concern (Iglesias et al. 2008b; Garrote et al. 2015; Iglesias and Garrote 2015). Coastal systems are expected to experience adverse impacts due to the foreseen sea level rise (e.g., coastal flooding, coastal erosion, salt water intrusion and water quality worsening; IPCC 2014a; Ramieri et al. 2011). Further, the competition and conflicts among stakeholders (i.e., agriculture, natural ecosystems and society) will be increased due to a major pressure on natural resources as a result of these climate change impacts, increased population, pollution from agriculture intensification and fragmented and uncoordinated climate policy strategies (Iglesias 2009).

Responses to face climate change at farm level include two policy interventions: mitigation and adaptation. Mitigation refers to actions that reduce GHG emissions and enhance carbon sinks to limit long-term climate change. The EU targets to achieve GHG reductions commitments (by 20% in 2020; EC 2013a) include a large contribution of the agricultural sector, and at the same time, maintain the competitiveness of the sector (Van Doorslaer et al. 2015). Adaptation refers to actions that help agriculture and the environment to adjust to climate change consequences. Adaptation policy actions should not result into GHG emissions increases, and thus must consider their mitigation potential (Klein et al. 2007).

A comprehensive climate policy need to reach a balance among equity, economic security and the environment by farming and policy choices for global, regional and local scales that may deal with the increasing pressure on natural resources. Information on experimental evidence and resources to define and implement choices are key elements (e.g., what to adapt to and how to adapt; Füssel and Klein 2006). Farm management and technology uptake can strongly influence current farm performance and are likely to also influence adaptation to future changes and mitigation of agricultural emissions (Reidsma et al. 2010; Smith and Olesen 2010). Farming choices include a large range of technical, infrastructure, economic and social drivers and need to be assessed and interrelated to encourage their adoption and support the climate policy development (Iglesias and Garrote 2015). The concept of climate smart agriculture has emerged to encompass all these issues as a whole.

1.3 Objectives

The main objective of this research is to assess the potential farming and policy choices for mitigation and adaptation to climate change, focusing in the Mediterranean and specifically in two study areas of Spain. When assessing choices aimed at reducing threats to agriculture and the environment under climate change, two research questions arise: What information defines smart farming choices? What drives the implementation of smart farming choices? This Thesis tries to answer these questions to support climate policy development including both adaptation and mitigation.

This Thesis addresses the two research questions in four specific objectives as follows:

- To identify the critical temperature thresholds which impact on the growth and development of three major crops (i.e., rice, maize and wheat) to be used for modellers in climate crop simulations.
- To provide potential adaptation options that could improve the water supply reliability and in turn maintain the correct functioning of both the farming system and the natural ecosystem in a Mediterranean region where water resources are limited.
- To identify the most appropriate agronomic practices under different climate scenarios which result in an optimized balance between crop productivity and mitigation potential and to identify the main drivers that influence the adoption of these practices in a semi-arid region in the Mediterranean.
- To develop farming and policy tools to help to reach mitigation targets and enable farmers, advisors and policy makers to select the most appropriate and cost-effective practices for Mediterranean farming systems, soils and climates.

The areas of study considered in this Thesis are two Mediterranean regions in Spain, the Doñana coastal wetland (Southern Spain) and the Aragón region (North-eastern Spain).

The Doñana coastal wetland is a world heritage and biodiversity site (i.e., Ramsar Wetland, UNESCO World Heritage Site and Biosphere Reserve). It is located in the lower part of the Guadalquivir River Basin District in Southern Spain. The largest rice (*Oryza sativa L.*) farming area of the country (ca. 36,000 hectares) is located in the eastern side of the Doñana wetland. The water is shared among the intensive use for rice farming and the natural ecosystem. The two systems show a great dependence on water and climate and any alteration of these factors may change their good functioning and the local livelihood security (Iglesias et al. 2015). The recent high temperature and drought episodes and the need for adaptation options make this region a suitable case study for this Thesis.

The Aragón region is an intensive agricultural area located in north-eastern Spain in the middle of the Ebro river basin. Aragón is the fourth largest region of Spain with 4,770,054 ha and its land is largely dedicated to agriculture (10% of the Spanish agricultural area) with approximately 1,300,763 ha of crop land and 324,354 ha of pasture and grassland (MAGRAMA 2013). In Aragon, about 25% of the total agricultural land is irrigated. Irrigated areas are mainly located in the centre of the region where water-limiting conditions are present and mean annual precipitation ranges from 300 mm to 800 mm. At present, agricultural activities in Aragón are responsible for about 3.8 million tCO_2eq, over 20 % of total GHG emissions in the region and from which 1.85 million tCO_2eq are released just by crop cultivation (MAGRAMA 2012). In most cases, the current agricultural management is based on intensive tillage, high mineral and organic fertilization and the use of monocultures (Álvaro-Fuentes et al. 2011). Consequently, small changes in the current management could have large potential for improving regional and national mitigation commitments (Sánchez et al. 2014a). The Aragón region is a suitable case study for this Thesis since it exemplifies semiarid Mediterranean agricultural systems and provides realism to the mitigation analysis.

1.4 Structure of the Thesis and Publications

This Thesis is structured in seven chapters. The first chapter contains a general introduction, setting the research context, the objectives and the issues that are going to be addressed in this work. Chapter 2 summarises the state of the art. Chapters 3 to 6 contain the main original and empirical contributions of the Thesis into four studies, which in turn interact and feedback. Because each one has its own objectives, scope and methods, they are organized canonically with an introduction and subsequent sections containing the methodology, results, discussion and conclusions respectively. They illustrate the multidisciplinary methods and tools applied to explore strategic farming choices to respond to mitigation and adaptation to climate change. Chapter 7 presents the main conclusions obtained in this doctoral research. The Annexes 1 to 5 present additional information supporting the data and results. Figure 1.1 outlines the research context and Table 1.1 the list of publications of the Thesis.

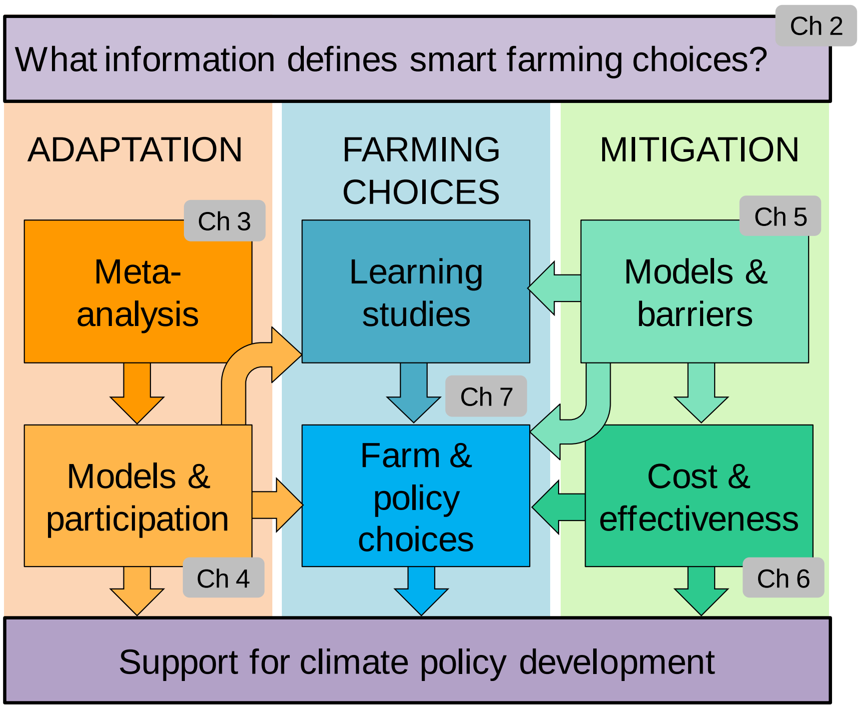

Figure 1.1. Links between the research methods and the structure of the Thesis

Table 1.1. List of publications

Components of the Thesis, Objectives and Publications

I: Meta-analysis of crop responses to climate (Chapter 3)

Objective

Identification of the critical temperature thresholds which impact on the growth and development of three major crops

Publication in JCR journal

Sánchez B, Rasmussen A, Porter JR (2014) Temperatures and the growth and development of maize and rice: a review. Global Change Biology, 20(2), 408-417. DOI: 10.1111/gcb.12389

II: Adaptation: models and participatory methods (Chapter 4)

Objective

Identification of potential adaptation options for improving water scarcity

Publication in JCR journal

Iglesias A, Sánchez B, Garrote L, López I (2015) Towards adaptation to climate change: water for rice in the coastal wetlands of Doñana, Southern Spain. Water Resources Management, 1-25. DOI: 10.1007/s11269-015-0995-x

Book Chapter

De Stefano L, Hernandez Mora N, Iglesias A, Sánchez B (2014) Water for rice farming and biodiversity: exploring choices for adaptation to climate change in Doñana, southern Spain. In: Stucker D and Lopez-Gun E (Eds.) Adaptation to Climate Change through Water Resources Management: Capacity, Equity, and Sustainability. Oxford, UK: Routledge / Earthscan.

Conference Proceedings

Sánchez B, Iglesias A (2012) Spanish case study: Impacts of climate change on agriculture in Spain. WWF-Spain Training on Climate Change Adaptation, Madrid, Spain, 26-27th January 2012

Sánchez B, Iglesias A (2014) Implications of climate change for rice farming in the Doñana wetland (SW Spain). WETLANDS 2014. Wetlands Biodiversity and Services: tools for the socio-ecological development, Huesca, Spain, 14-18th September 2014

III: Drivers and barriers to adoption of mitigation practices (Chapter 5)

Objective

Exploring the most appropriate agronomic practices that optimize crop productivity and have mitigation potential

Publication in JCR journal

Sánchez B, Álvaro-Fuentes J, Cunningham R, Iglesias A (2014) Towards mitigation of greenhouse gases by small changes in farming practices: understanding local barriers in Spain. Mitigation and Adaptation Strategies for Global Change, 1-34. DOI: 10.1007/s11027-014-9562-7

Conference Proceedings

Sánchez B, Álvaro-Fuentes J, Cunningham R, Iglesias A (2013) Mitigation by small changes in farmers' practices: evaluation of local incentives to inform European policy. IX Spanish National Congress of Agricultural Economics, Castelldefels, Spain, 3-5th September 2013

Sánchez B, Álvaro-Fuentes J, Cunningham R, Iglesias A (2013) Farmers' response to mitigation practices in Spain. Remedia Second Workshop, Zaragoza, Spain, 11-12th April 2013

Continued in the next page

Chapters of the Thesis, Objectives and Publications (Cont)

IV: Cost effectiveness and policy choices (Chapter 6)

Objective
Supporting farming and policy tools for mitigation

Publication in JCR journal
Sánchez B, Iglesias A, McVittie A, Alvaro-Fuentes J, Ingram J, Mills J, Lesschen JP, Kuikman P (2015) Cost-effective management of agricultural soils for greenhouse gas mitigation: Learning from a case study in NE Spain, Journal of Environmental Management (in review)

Publications in policy journals
Ingram J, Mills J, Frelih-Larsen A, Davis M, Merante P, Ringrose S, Molnar A, Sánchez B, Ghaley BB, Karaczun Z (2014) Managing Soil Organic Carbon: A Farm Perspective. EuroChoices, 13(2), 12-19. DOI: 10.1111/1746-692X.12057

Conference Proceedings
Sánchez B, Iglesias A, McVittie A, Alvaro-Fuentes J, Ingram J, Mills J, (2015) Marginal abatement cost and stabilization wedges of greenhouse gas mitigation from small changes in crop management in NE Spain. 6th EAAE PhD Workshop, Rome, Italy, 8-10th June 2015
Sánchez B, Iglesias A, Álvaro-Fuentes J (2015) Exploring strategic management of agricultural soils for greenhouse gas mitigation: Stabilization wedges in NE Spain. Remedia Fourth Workshop, Madrid, Spain, 23-25th March 2015
Iglesias A, Sánchez B (2015) Exploring strategic management of agricultural systems to link mitigation and adaptation to climate change. 3rd Global Science Conference on Climate-Smart Agriculture, CSA2015, Montpellier, France, 16-18th March 2015
Sánchez B, McVittie A, Iglesias A, Álvaro-Fuentes J (2014) How much might Spanish farmers contribute to Mitigation?. Remedia Third Workshop, Valencia, Spain, 10-11th April 2014

SmartSOIL project Deliverables
Sánchez B, Medina F, Iglesias A, Lesschen JP, Kuikman P (2013). Typical farming systems and trends in crop and soil management in Europe. Deliverable 2.2 for EU SmartSOIL project, European Commission, Brussels. Available at http://smartsoil.eu/

2. State of the Art

This section provides the background for the general issues and aspects of the Thesis. The specific state of the art and the methods used are included in each relevant Chapter.

2.1 Climate change and socio-economic drivers

According to the Fifth Assessment Report (AR5) published by the IPCC in 2014, warming of the climate system is unequivocal. Global-scale observations in the climate system provide evidence on increases of global mean temperature (surface and ocean), widespread melting of snow and ice, sea level rise and increases of greenhouse gas concentrations (IPCC 2013). Increased human-made atmospheric gases, mainly CO_2, are predominantly causing alterations in the climatic systems (IPCC 2007a).

During the last 40 years, about half of cumulative anthropogenic CO_2 emissions have occurred and now substantially exceed the highest concentrations recorded (IPCC 2013). Cumulative CO_2 emissions have been released to the atmosphere mainly from fossil fuel combustion, cement production and flaring (420±35 $GtCO_2$ in 1750 to be tripled to 1300±110 $GtCO_2$ in 2010) and from anthropogenic land use change (490±180 $GtCO_2$ in 1970 to 680±300 $GtCO_2$ in 2010) (IPCC 2013). From 2000 to 2010, the total anthropogenic GHG emissions were the highest in human history and reached 49 (±4.5) $GtCO_2$eq/yr in 2010 (IPCC 2014b).

Long-term climate trends for the period 1950 onwards show changes in the frequency and magnitude of both moisture and temperature (IPCC 2014a), drying has been observed in Southern Europe, melting of the permafrost and ice sheets in Northern Europe, and changes in crop and ecosystems phenology in all regions (Easterling et al 2000; Walther et al. 2002; Iglesias 2012a). These trends will continue in the future even if greenhouse gas emissions are reduced to the minimum due to the atmosphere's inertia (Hansen et al. 2013). In the 21st century, it is clear that many regions are liable to suffer serious harm and many are already beginning to appear (IPCC 2014a).

Observed and predicted impacts of climate change on agriculture are different depending on the region and the analysed scale (global, regional or local). The potential consequences of climate change will produce beneficial impacts in some regions and harmful ones in others (IPCC 2007b). There are many studies on the implications of climate change over the agricultural sector (Rosenzweig and Iglesias 1994; Olesen and Bindi 2002; Lobell and Field 2007; Iglesias et al. 2012a) that also reflect the concern about potential consequences on poverty rates and sustainable development in the most marginal areas (Rosenzweig and Parry 1994; Parry et al. 2004; Mendelsohn et al. 2006; Stern 2007; Iglesias et al. 2011a).

The concentration of greenhouse gases in the atmosphere will determine the future climate (IPCC 2013). In turn, greenhouse gas emissions caused by human activities will depend on socioeconomic drivers such as land use, population and economic growth and energy technology among others (Stern 2007; Moss et al. 2010). Globally, economic and population growth are the most important drivers of increases in CO_2 emissions from fossil fuel combustion and the economic growth is rising sharply (IPCC 2014b). In 2010, the total anthropogenic GHG emissions released by different economic sectors were 49 (±4.5) $GtCO_2eq/yr$ (Figure 2.1).

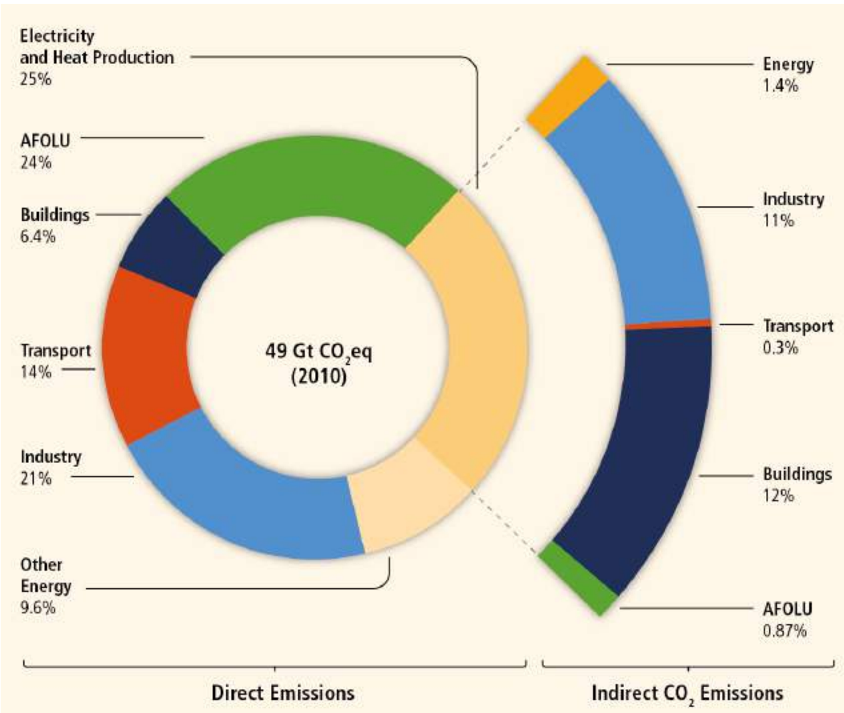

Figure 2.1. Greenhouse gas emissions by economic sectors in 2010 (IPCC 2014b)

The different economic sector contributed to the annual anthropogenic GHG emissions as follows: (a) accounting for direct emissions 35% (17 $GtCO_2eq$) of GHG emissions were released in the energy supply sector, 24% (12 $GtCO_2eq$, net emissions) in AFOLU (Agriculture, Forestry, and Other Land Use), 21% (10 $GtCO_2eq$) in industry, 14% (7.0 $GtCO_2eq$) in transport and 6.4% (3.2 $GtCO_2eq$) in buildings; (b) accounting for indirect emissions the industry and buildings sectors are increased to 31% and 19%, respectively (IPCC 2014b). Agricultural emissions from livestock and soil and nutrient management contribute to approximately half of the anthropogenic GHG emission (5.0-5.8 $GtCO_2eq/yr$) of the AFOLU, which in turn represents a quarter of the global GHG emissions (IPCC 2014b).

2.2 Climate change scenarios

Scenarios are pictures of the future or alternative futures, they are neither forecasts nor projections (Moss et al., 2010). Each scenario represents a picture about how future can change. There is certain uncertainty associated to the climate change scenarios, however they are capable to represent potential futures based on different assumptions and enhance the understanding on the Earth´s natural system development (Stainforth et al., 2005). The scenarios can be useful tools for the climate change analysis, including climate modelling, impact assessment and potential mitigation and adaptation measures (van Vuuren et al 2011b).

A number of contrasting scenarios are usually generated to define a realistic range of potential futures by representing different projections. The new climate change scenarios are generated based on the following types of models and analytic frameworks (Figure 2.2; Moss et al. 2010; van Vuuren et al. 2013): (a) a set of four new pathways, representative concentration pathways (RCPs) based on previous experimental evidence to provide needed inputs of emissions, concentrations and land use/cover for climate models (van Vuuren et al. 2011a); (b) new socioeconomic and policy scenarios that determine GHG emissions (e.g., the Shared Socioeconomic Pathways, SSPs; van Vuuren and Carter 2013; O’Neill et al. 2014) based on a set of drivers such as demography, energy use, technology, the economy, agriculture, forestry and land use. Some of these socioeconomic scenarios are consistent with the radiative forcing characteristics used to identify the RCPs and some to explore completely different futures (Moss et al. 2010); (c) global climate models (GCMs) based on physical and chemistry assumptions that determine the Earth's natural systems to study how climate responds to changes in natural and human-induced perturbations (e.g., atmosphere-ocean general circulation models can simulate interactions of the atmosphere, ocean, land and sea ice; Moss et al. 2010); and (d) integrated assessment of climate and socioeconomic scenarios to evaluate impacts, adaptation and vulnerability to climate change that include both quantitative and qualitative approaches based on assumptions made to regionalize (downscaling) the results of global models (van Vuuren et al. 2011b).

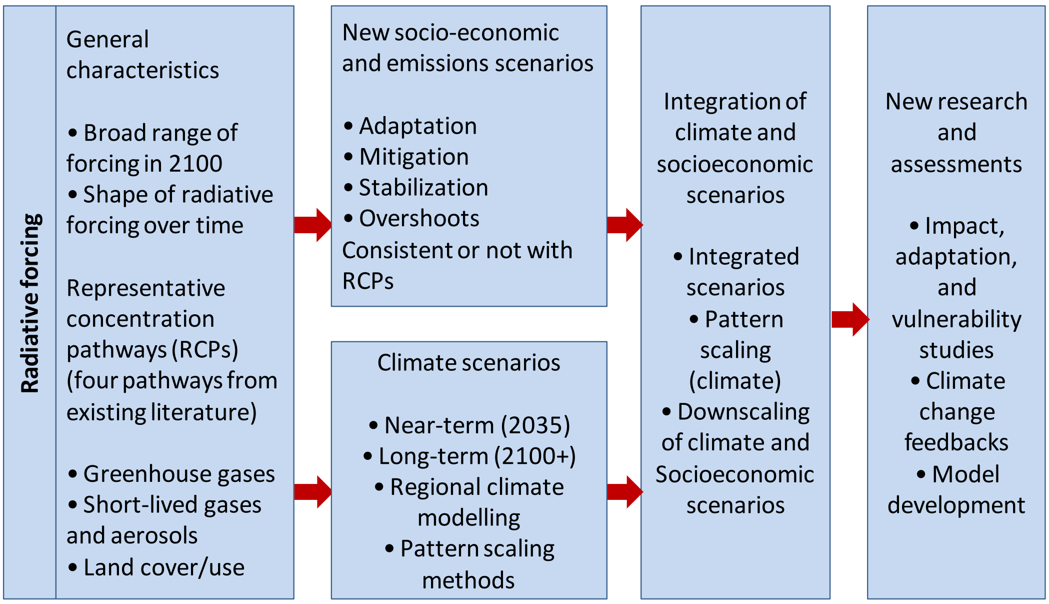

Figure 2.2. The process of developing the new climate change scenarios of the IPCC. Adapted from Moss et al. (2010)

The four RCPs (i.e., RCP2.6, RCP4.5, RCP6.0 and RCP8.5) span together the range of year 2100 radiative forcing values from 2.6 to 8.5 W/m^2, including GHGs, tropospheric ozone, aerosols and albedo change, and are supplemented with extensions (Extended Concentration Pathways, ECPs; van Vuuren et al. 2011a). Figure 2.3 shows the atmospheric concentration levels and GHG emissions projections for the four RCPs (IPCC 2014c). The CO_2eq concentration in 2011 is estimated to be 430 parts per million, ppm (uncertainty range 340–520 ppm). Baseline scenarios (without additional efforts to constrain emissions) exceed 450 and 750 to 1300 ppm CO_2eq by 2030 and 2100 respectively. It is similar to the range in atmospheric concentration levels between the RCP6.0 and RCP8.5 pathways in 2100. Increases projected of global mean surface temperature under the four RCPs are likely to be 0.3-1.7°C (RCP2.6), 1.1-2.6°C (RCP4.5), 1.4-3.1°C (RCP6.0) and 2.6-4.8°C (RCP8.5) by the end of the 21st century (IPCC 2014c). Changes in precipitation will not be uniform among latitudes under RCP8.5 scenario; increases in annual mean precipitation are likely to be placed in high latitudes, mid-latitude wet regions and the equatorial Pacific and decreases in many mid-latitude and subtropical dry regions (IPCC 2014c).

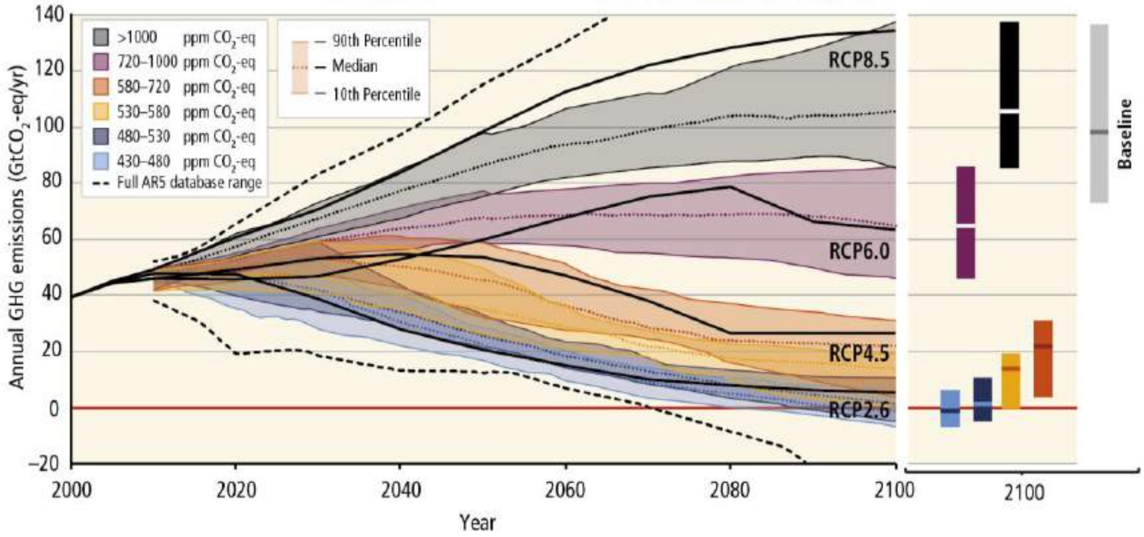

Figure 2.3. GHG emission pathways 2000–2100 (gigatonne of CO_2-equivalent per year, GtCO2-eq/yr) of the four RCPs scenarios for different long-term concentration levels (IPCC 2014b)

2.3 Climate change policy and the agricultural sector

Article 2 of the United Nations Framework Convention on Climate Change in 1992 (UNFCCC) expresses: "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner". In December 1997 the UNFCCC adopted the Kyoto protocol which establishes legally binding limits for industrialized countries on emissions of carbon dioxide and other greenhouse emissions (Breidenich et al. 1998). In 2002 the Kyoto Protocol was ratified and the European Union (EU) has remained at the forefront of the efforts to reduce GHG emissions amongst developed economies (Domínguez and Fellmann 2015).

There are two policy options to reduce threats and risks posed by anthropogenic climate change (Füssel and Klein 2006): mitigation of climate change which refers to reducing the GHG emissions and enhancing their sinks; and (2) adaptation to climate change which refers to reducing the harms of unavoided climate change by a wide range of adaptation actions targeted at vulnerable systems.

The European Union goals to achieve GHG mitigation include a large contribution of the agricultural sector and at the same time maintain the competitiveness of the sector. A recent study (Van Doorslaer et al. 2015) presents an overview of the historical and projected development of agricultural GHG emissions in the EU, concluding that: (a) agriculture accounted for 10% of total EU GHG emissions in 2011; and (b) the largest part of the required GHG reduction may be realised by reducing livestock production and implementing best cropland measures.

The European policy agenda and EU Member States have just started to develop National Adaptation Strategies (NASs) which include strategies to the agricultural sector. Biesbroek et al. (2010) found in seven National Adaptation Strategies adopted at the end of 2008 that in most cases approaches for implementing and evaluating the adaptation strategies are yet to be defined. Adaptation has been less developed than mitigation, from both the scientific and policy perspective (Burton et al. 2002). Information on what to adapt to and how to adapt and resources to implement the adaptation measures are key elements of a comprehensive climate policy (Füssel and Klein 2006).

2.3.1 Adaptation of the agricultural sector to climate change

Adaptation refers to actions that help agriculture and the environment to adjust to climate change consequences. Adaptation strategies to improve the adaptive capacity of crop production to climate change are necessary, since crop production demand will increase, and higher temperatures, heat waves, droughts and floods will become more frequent and extreme under all assessed emission scenarios (Iglesias et al. 2011b; IPCC 2014c). The effects of climate variables, most notably temperature, are already significant to the crop production output and efficiency, as well as regional differences in adaptive capacity (Bardají and Iraizoz 2015). Changing precipitation or melting snow and ice are altering hydrological systems in many regions, affecting water resources in terms of quantity and quality and shifting geographic ranges, seasonal activities and migration patterns of freshwater and marine species (IPCC 2014c; Iglesias and Garrote 2015).

The impacts of climate change also depend on the adaptation response at the farm and policy level. Several hundred studies have assessed impacts and adaptation of crop production to climate change covering a wide range of European regions and crops (Olesen and Bindi, 2002; Ewert et al. 2005; Reidsma et al. 2010; Olesen et al. 2011; Iglesias et al. 2011a, 2012a, 2012b; Bardají and Iraizoz 2015; Garrote et al. 2015). The negative impacts of climate change on crop yields are expected to be more common than positive impacts in most of regions (Iglesias et al. 2012a; IPCC 2014a).

Policy will have to support the adaptation of European agriculture to climate change by including investing in monitoring schemes, early warning systems and crop breeding (Olesen et al. 2011; Iglesias and Garrote 2015). Policy will also need to link the needs for adaptation with agricultural strategies to reduce GHG emissions, increase soil carbon sequestration and the growing of energy crops to substitute fossil energy use (Smith and Olesen 2010). Adaptation policy actions should not result into GHG emissions increases, and thus must consider their mitigation potential (Klein et al. 2007). Adaptation and mitigation policies have to be linked closely to the development of agri-environmental schemes in the EU Common Agricultural Policy (CAP; Bardají and Iglesias 2014).

Further, socio-economic conditions, farmer behaviour and farm management can strongly influence current farm performance and adaptation to future changes (Reidsma eta al. 2010). Multidisciplinary problems require multidisciplinary solutions, including adaptation assessment frameworks that integrate and are easily operated by all stakeholders, practitioners, policymakers, and scientists (Howden et al. 2007; Varela-Ortega et al. 2013).

2.3.2 Mitigation of GHG emissions in the agricultural sector

Mitigation is a human intervention to reduce the sources or enhance the sinks of greenhouse gases. Emission pathways that lead to different GHG concentrations have been defined in detail at the global level (Moss et al., 2010). There are multiple scenarios with a range of technological and behavioral options, with different characteristics and implications for sustainable development, that are consistent with different levels of mitigation (IPCC 2014b). The EU has a clear goal to reduce the GHG emissions by 20% in the next ten years, and the mitigation goals are accompanied by a set of policies (EC 2013a). The Common Agricultural Policy of the EU (CAP) includes since 2013 mitigation policies in the called "greening" (Bardají and Iglesias 2014).

The AFOLU sector contributes for about a quarter of net anthropogenic GHG emissions (12 $GtCO_2eq/yr$) mainly from deforestation and agriculture emissions (IPCC 2014b). Agricultural emissions from livestock and soil and nutrient management contribute to approximately half of the anthropogenic GHG emission of the AFOLU sector (5.0-5.8 $GtCO_2eq/yr$). However, the AFOLU sector is expected to become a net CO_2 sink by the end of century, since it plays a central role for implementing the most cost-effective mitigation options in forestry (e.g., afforestation, sustainable forest management, reducing deforestation) and agriculture (e.g., cropland management, grazing land management, restoration of organic soils; IPCC 2014b).

The Kyoto Protocol in the United Nations Framework Convention on Climate Change recognised the role of agricultural management to provide soil organic carbon (SOC) sequestration (UNFCCC 2008). The reductions of agricultural emissions to achieve the EU target depend on the quantitative details of mitigation potential and cost of the management at the farm level, the barriers to behavioural change and the agricultural policy that influences farmers' decisions (Smith et al. 2007a; Stern 2007; OECD 2012b).

Several management actions to sequester SOC in cropland soils which benefit soil carbon stocks and, in turn, optimise crop productivity, have been widely recognised (Freibahuer 2004; Smith et al. 2012; Aguilera et al. 2013; Lal 2013). These options include, among others: reduced and zero tillage; perennial and deep rooting crops; a more efficient use of resources and integrated nutrient managements with organic amendments and compost; improved rotations; cover crops; improved irrigation management; organic farming; legumes/improved species mix; residue management; and land-use change (conversion to grass/trees). In spite of global estimations of the SOC sequestration potential can be overestimated in some local conditions (Lam et al. 2013; Powlson et al. 2014; Derpsch et al. 2014), it is clear that smart soil management leads to improve soil health, reduce soil degradation and GHG emissions (Lal 2013).

2.4 Measuring crop responses to climate: Tools and methods

Farmers have to make decisions based on factors such as weather, prices and markets which are associated with high levels of uncertainty. In most cases, farmers make decisions according to their knowledge of the past to estimate, or at least perceive, the risk probabilities to production (McCown 2002).

Changes in crop productivity are difficult to predict but can be explored by scenarios that represent alternative economic and environmental pathways of future development (Ewert et al. 2005). The uncertainty of prediction will depend on the data used to build agro-climatic models and how methodological approaches integrate farmer behaviour and policy choices in the assessment (e.g., technology, management and agricultural policy). This section provides a background of the recent studies that evaluate future crop production including the methods of assessment, i.e., experimental evidence, models, and participatory approaches.

2.4.1 Experimental evidence of crop responses to relevant factors

Crop productivity is affected by climate, atmospheric composition, soils, pests and diseases, farm management and technology, and water management among others. These determinants are discussed below.

Climate

Extreme events and variability in temperature, rainfall and solar radiation can disrupt crop yields and are key factors of crop productivity (Brown and Rosenberg 1997). However, crops often respond nonlinearly to changes in their growing conditions and have threshold responses, which increase the importance of climate variability for yield stability and quality (Porter and Semenov 2005). Thus, increases of climate variability will result in higher yield variability. In addition to the linear and nonlinear responses of crop growth and development to the variations in temperature and rainfall, short-term extreme temperatures can have large yield-reducing effects (Porter and Semenov 2005). During flowering periods, where short-term exposure to high temperatures (usually above 35 °C) can greatly reduce spikelet fertility and therefore yield. Exposure to drought during these periods may have similar effects (Barnabás et al. 2008; Iglesias et al. 2008a). A close relation between the intensity of solar radiation and temperature is observed affecting yields levels in tropical and subtropical regions, and in a less extent, in temperate zones (Brown and Rosenberg 1997).

Higher climate extreme events are projected to take place by the middle of this century (IPCC 2013). Similar consequences can be illustrated by the impacts of the European heat wave of August 2003 (Beniston and Stephenson 2004), when the combination of high temperatures and deficits in rainfall led to reductions in crop and livestock production for about €11 billion in central and southern Europe. Thus, there is a need of further research on how crops response to climate extreme events and variability.

Atmospheric composition

According to the IPCC (2013), atmospheric CO_2 concentration levels are increasing alarmingly. In 2005 the CO_2 measure was 379 ppm, an increase over 100 ppm since 1750. Indirectly, these figures are leading to the global warming and they are encouraging the faster appearance of extreme events.

Several experiments have shown that the most important source of CO_2 for crops photosynthesis is the atmosphere (Yoshida 1981). CO_2 enrichment of air increases the growth and yield of plants, but it seems to vary between C3 and C4 species. C3 species may increase growth and the optimum temperature for photosynthesis, whereas C4 species may be scarcely affected by CO_2 concentration (Long et al. 2004). The photosynthetic rate of C3 species is increased with elevated CO_2 due to higher carboxylation and lower oxygenation (Long et al. 2004). Carbon dioxide enrichment is usually favourable for rice plants and C3 species due to increase of carbon dioxide assimilation rates and final grain yield (Baker 2004).

Soils

Soils have many functions, including the essential supply of water and nutrients to growing crops and habitats for many organisms that contribute in turn to the functioning of soils (Alcamo and Olesen 2012). Soils are relevant for regulating greenhouse gas emissions since they are one of the most important terrestrial pools for carbon storage and exchange with atmospheric CO_2 (Follett 2001). In addition, many agricultural soils are degraded due to salinization form inadequate irrigation practices and tillage, loss of organic matter due to high temperatures and soil structure loss due to high winds (Lal 2013).

Pests and diseases

Increases of temperature allow the proliferation of insect pests, since many insects can complete a greater number of reproductive cycles (Bale et al. 2002). Warmer winter temperatures may also allow pests to overwinter in areas where they are now limited by cold, thus causing greater and earlier infestation during the following crop season (Alcamo and Olesen 2012). Thus, climate warming will lead to earlier insect spring activity and proliferation of some pest species (Alcamo and Olesen 2012).

Farm management and technology

Farm management and technology uptake can strongly influence current farm performance and are likely to also influence adaptation to future changes and mitigation of agricultural emissions (Reidsma et al. 2010; Smith and Olesen 2010). Many of the options are based on well tested agronomic and technical know-how, with proven benefits for farmers and the environment (Smith et al. 2008, 2012). However, the motivations of farmers to the implementation of new technologies and management options are mainly driven by short to mid-term productivity or economic considerations and there are important barriers to the uptake (e.g. social acceptance, strong traditions, work load and costs among others; Ingram et al. 2014). Farmers will not adopt unprofitable practices in the absence of regulations or incentives and additional support will be needed for farmers to adopt these practices including education, demonstration and advice (Smith and Olesen 2010).

Water management

Water is considered as an important factor to get higher yields and as a limiting factor under conditions of water scarcity or drought. Thus, water availability at the regional scale is the main determinant of crop production. Climate change is expected to intensify the existing risks, particularly in regions where water scarcity is already a concern, and water management for agriculture will become more complex (Iglesias and Garrote 2015). Severe drought and changes in rainfall will affect the water availability for crop production, especially in Mediterranean (IPCC 2014a). Choices for agricultural water management include a large range of technical, infrastructure, economic and social factors and need to be inter-related not only to traditional water resources management, but also to food production, rural development and natural resources management (Iglesias and Garrote 2015).

2.4.2 Agricultural models

As mentioned before, to study appropriately the effect of extreme events on growth and development of crops, modelling tools should take into account factor such as physiology (effects of CO_2, high/low temperature), farm management (soils, water management, fertilization) and the ability to interrelate each other. There are a number of different models and indices to improve accuracy and allow inter-comparison of the results and they need to be applied also at local and regional scales (Rötter et al. 2011).

Agricultural models analyze information for different types of impacts. For example, simple agro-climatic indices can be used to analyze large area shifts of cropping zones, whereas process-based crop growth models are used to analyze changes in crop yields.

Effects on production, income, or employment are assessed using economic and social analysis as discussed in the following section.

Agro-climatic indices

The agro-climatic indices are based on simple relationships of crop suitability and climate determinants (e.g., identifying the temperature thresholds of a given crop or using accumulated temperature over the growing season to predict crop yields; Porter and Gawith 1999; Sánchez et al. 2014b; Trnka et al. 2011). These models are especially useful for effective analysis of agroclimatic indicators under climate change conditions for a particular region.

Process-based crop models

Process-based crop models use functions to evaluate the impacts of weather and climate variability (climate, soils and management) on crop growth and production, especially at a large scale (Tao et al. 2009). Dynamic crop models are now available for most of the major crops with the aim to predict the response of a given crop to specific climate, soil and management factors (Lobell and Field 2007).

Production functions

Statistical models may be developed from empirical data or from a combination of empirical data and simulated data that represents the causal mechanisms of the agricultural responses to climate. Multivariate statistical models attempt to provide a statistical explanation of observed phenomena taking into account relevant and common factors (e.g., predicting crop yields on the basis of temperature, rainfall, sowing date and fertiliser application).

Current modelling communities prefer process-based models over empirical tools, however, empirical crop growth models can play an important role in identifying crop growth processes relating to a wide range of land management options (Park et al. 2005). Iglesias et al. (2012a) have followed a combination approach of process-based models and statistical functions of yield response to develop crop production functions across Europe for policy analysis.

Economic models

Economic studies on climate change effects contain assumptions on future emissions and other aspects of climate to translate them into economics consequences (Tol 2009).

Several economic approaches have been used in order to estimate the potential impacts of climate change on agricultural production, consumption, income, gross domestic product (GDP), employment, and farm value based on the integration of biophysical and agro-economic models (Parry et al. 2004; Fischer et al. 2005; Fernández and Blanco 2015). Microeconomic models based on the goal of maximizing economic returns to inputs have been used extensively in the context of climate change (Antle et al. 2001).

Integrated models

The implications of climate change for the environment and society will depend on how humankind responds through changes in technology, economies, lifestyle and policy (Moss et al. 2010). There is a need to compromise accuracy at regional level in order to achieve integrated approaches for policy-makers and practicioners. Some integrated assessment models are especially relevant for food analysis production since they can link agriculture, land use, water, environment and socio-economic factors (Rötter et al. 2011).

Uncertainty of the models of crop production

The crop models contain many simple, empirically-derived relationships that do not completely represent actual crop processes. Current crop models do not incorporate the latest knowledge about how crops respond to a changing climate and may not properly represent modern crop varieties and management practices. Quantification of complex interactions (crop, climate and soil) is essential for supporting farming management strategies and policy decisions at multiple scales (Rötter et al. 2011).

In terms of research, necessary actions to decrease uncertainty in crop modelling are needed, starting by reviewing deficiencies in existing models, making efforts to compile high-quality field data and compare results as a vital tool in testing uncertainty (Rötter et al. 2011). When models are adequately tested (calibration and validation process), these result can promote more reliable information to make easier the decisions of policy maker.

2.4.3 Participatory methods

Assessing impacts and strategic farming choices to respond to climate change depends on a wide array of methods and tools that includes both quantitative and qualitative approaches (Moss et al. 2010). Prominent approaches include observations, modelling, assessment techniques that engage stakeholders in participatory processes, economic evaluation methods and decision analysis.

The participatory processes and methods are a powerful strategy to advance both science and practice by involving practitioners in the research process through primary data gathering (e.g., surveys and interviews, focus groups, expert panel) and analysis (e.g., interpretive techniques; multi-criteria decision analysis, econometric models; factor analysis ; Freeman 1984; Whyte 1991; Glicken 2000). Mitigation and adaptation assessment approaches need to be integrated by all stakeholders, practitioners, policymakers, and scientists (Howden et al. 2007). Those are likely to be affected by climate change risks and local communities are expected to be on the frontline of damaging climate impacts (Ross et al. 2014).

Climate change assessments are complex and require an integrated approach involving communities and all levels in the decision analysis. The implications of climate change need to be interpret at local levels in ways that have local meaning. Agriculture is a science which requires experience and technical inputs needs to be carefully detailed to support, rather than dominate the participatory process (Rauschmayer and Wittmer 2006). Moreover, the changing socio-economic and environmental conditions linked with climate change will require complex considerations to find the most appropriate responses (Glicken 2000). Consultation with farmers allows overcoming possible barriers and can help to link science to policy by understanding local decision making and behavior with respect to innovative management (Freeman 1984). Insights from previous work have shown that, although economic incentives are important, local decisions are also related to other socio-economic factors such as farm size, technology, agri-environmental schemes, and local attitudes and traditions (Sánchez et al. 2014a).

3. Meta-analysis of the effect of temperature on crops

Publication: Sánchez B, Rasmussen A, Porter JR (2014) Temperatures and the growth and development of maize and rice: a review. Global Change Biology, 20(2), 408-417. DOI: 10.1111/gcb.12389

Objective: To identify the critical temperature thresholds which impact on the growth and development of three major crops (i.e., rice, maize and wheat) to be used for modellers in climate crop simulations.

Contribution: B. Sánchez was the lead author and wrote the paper. She carried out the rice meta-analysis and interpreted the results of the three crops.

3.1 Abstract

Because of global land surface warming, extreme temperature events are expected to occur more often and more intensely, affecting the growth and development of the major cereal crops in several ways, thus affecting the production component of food security. In this paper, we have identified rice and maize crop responses to temperature in different, but consistent, phenological phases and development stages. A literature review and data compilation of around 140 scientific articles have determined the key temperature thresholds and response to extreme temperature effects for rice and maize, complementing an earlier study on wheat. Lethal temperatures and cardinal temperatures, together with error estimates, have been identified for phenological phases and development stages. Following the methodology of previous work, we have collected and statistically analysed temperature thresholds of the three crops for the key physiological processes such as leaf initiation, shoot growth and root growth and for the most susceptible phenological phases such as sowing to emergence, anthesis and grain filling. Our summary shows that cardinal temperatures are conservative between studies and are seemingly well-defined in all three crops. Anthesis and ripening are the most sensitive temperature stages in rice as well as in wheat and maize. We call for further

experimental studies of the effects of transgressing threshold temperatures so such responses can be included into crop impact and adaptation models.

Keywords: maize, rice, lethal temperatures, cardinal temperatures, growth, development, climatic change impacts.

3.2 Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment has forecast that the increase in global average temperature will between 1.8 to 4.0ºC in 2100, depending on the level of greenhouse gas emissions. The increase can even be larger (perhaps up to 6.4ºC) if the human population and the global economy continue growing at their current rates. An increase of 2-3ºC in global average temperature is predicted if CO_2 levels stabilise around 450 ppm (IPCC 2007a).

Changes to the global climate, notably to regional spatial and temporal temperature patterns from increased atmospheric concentrations of greenhouse gases are predicted to have important consequences for crop production (Parry *et al*. 2004; Lobell & Field, 2007). Both plant growth and development are affected by temperature (Stone, 2001; Barnabás *et al*. 2008). Investigations of the effects of changes in mean annual temperature on agricultural crops (Wheeler *et al*. 2000; Challinor *et al*. 2007) have used crop-climate simulation models (Lobell *et al*. 2012; Hawkins et al. 2012) and experiments (Wheeler *et al.* 1996b; Lobell et al. 2011). Impacts of mean temperature changes on crops preceded consideration of the effects that changes in climatic variability and extreme conditions might have. A changing or changed climate may exhibit increased climatic variability and small changes in climatic variability can produce relatively large changes in the frequency of extreme climatic events (Porter & Semenov, 2005).

This paper reviews the threshold temperature literature for maize and rice, complementing an earlier study for wheat (Porter & Gawith, 1999). Our primary purpose is to synthesise available results and make this information more accessible to the climatic change community, allowing identification of whether the frequency of extreme temperature events that affect crop production is either changing or will change under climate change. This may include increases in the frequency of discrete events such as plant mortality caused by low or high temperatures. Less extreme but still important temperature changes may increase plant sterility and reduce grain set. We hope that modellers can use the data presented to assess quantitatively the effects of temperature change on crop processes.

In our literature review we describe the responses of maize and rice plants to extreme temperatures under experimental conditions. Cardinal temperature thresholds for different phenological processes are identified and we outline the effects of temperature on rates of growth and development. Finally, we assess the implications of the above for future climatic impact studies.

3.3 Materials and methods

For both crops we estimated the minimum, optimum and maximum temperatures (termed the cardinal temperatures) plus their standard errors (s.e.) for the following processes: mortality, leaf initiation, shoot growth, root growth and crop development for the following phenological phases and stages: germination and emergence, tillering (rice), panicle (rice) or ear (maize) initiation, anthesis, grain filling and the whole plant life-cycle.

We collected literature reporting temperatures for these processes, phenological phases and stages from field, laboratory and experimental greenhouse studies. About 70 articles were selected from the reviewed literature for each of the two crops species: rice (*Oryza sativa* L.) and maize (*Zea mays* L.). Temperature data were extracted from the articles and classified into three thresholds according to the following criteria: (i) Optimal temperature (Topt), defined as the temperature giving the highest rate of a crop process; (ii) Minimum or base temperature (Tmin) defined as the lower limits and (iii) maximum temperature (Tmax) defined as the upper limits at which plants suffered tissue injuries or where a physiological process may cease. In the case of cardinal temperatures, the plant did not suffer irreversible damage but has a possible recovery of function; lethal temperatures caused irreversible damage. Relevant literature from databases was downloaded, data extracted, sorted and presented in Tables A1.1 to A1.7 and references in Annex 1. Data are organised such that the three temperature thresholds (Tmin, Tmax, Topt) are evident, as are the cultivar used and the source of temperature data in the reviewed study. In the case of rice, we also specified sub-species (ssp. *japonica* or ssp. *indica*), when it was specified in the reviewed study.

We used the compiled data (n samples) to calculate the mean minimum, optimum and maximum temperatures by processes and phenological phases and stages for both crops. The standard errors of the mean (se) were calculated from the standard deviation of the compiled data used to estimate the mean. When temperature data were presented as interval and not as a specific temperature value, we calculated the arithmetic mean value of the interval. When values were defined as less (<) or greater than (>) a particular value, we calculated the mean and standard error of a cardinal value accordingly.

Limitations of our analysis are that differences exist between experimental designs leading to a confounding of the effects of different growing conditions, such as the relation between temperature and vapour pressure. Also, reported temperatures are normally ambient air and not actual plant temperatures. However, these limitations have also been the case in other recent papers examining plant temperature responses (Parent et al., 2010; Parent & Tardieu, 2012).

3.3.1 Wheat

Original data used to define and compare with cardinal temperatures for wheat (minimum temperature, Tmin; optimum temperature, Topt; maximum temperature, Tmax) are from Porter & Gawith (1999) and are in Table A1.7 (Annex 1).

3.3.2 Rice

Meta-data analysis of published material was assisted by the Faculty of Life Science library at the University of Copenhagen (http://www.bvfb.life.ku.dk). Most articles were found in the major scientific databases, such as Google Scholar, CAB Abstract, Web of Science, Agris and Agricola. A physical search was also made where necessary, especially as some of the literature dates from 1933 and much of the older literature is written in Chinese or Japanese without English text translation but with English summaries of figures and tables.

3.3.3 Maize

As with rice, a physical search was performed in specialist library at University of Copenhagen, Faculty of Life Sciences and a keyword search was performed in the major scientific databases/search engines including Web of Science, Agris, Agricola, Google Scholar, CAB Abstract and CAB reviews. The first identified reference came from Lehenbauer (1914), one of the first to make a scientific study of temperature and development in maize.

3.4 Results

Readers are asked to note that the original data used to provide the following summary results for rice and maize are available as complete dataset and references for the meta-analysis in Annex 1.

3.4.1 Wheat

Lethal limits for wheat were identified by Porter & Gawith (1999) as mean temperatures of -17.2ºC (s.e. 1.2ºC) for Tmin and 47.5ºC (s.e. 0.5ºC) for Tmax. They also reported temperature tolerances for different plants parts and phenological phases. Cardinal temperatures below 2ºC and higher than 25ºC (s.e. 5.0ºC) may accelerate roots senescence. Shoot elongation is slower at temperatures below *ca*. 20ºC and at temperatures higher than *ca*. 21ºC, being the mean minimum temperature 3.0ºC (s.e. 0.4 ºC). Leaf initiation is inhibited at a temperature of -1.0 (s.e. 1.1 ºC) (Figure 3.1a,b,c).

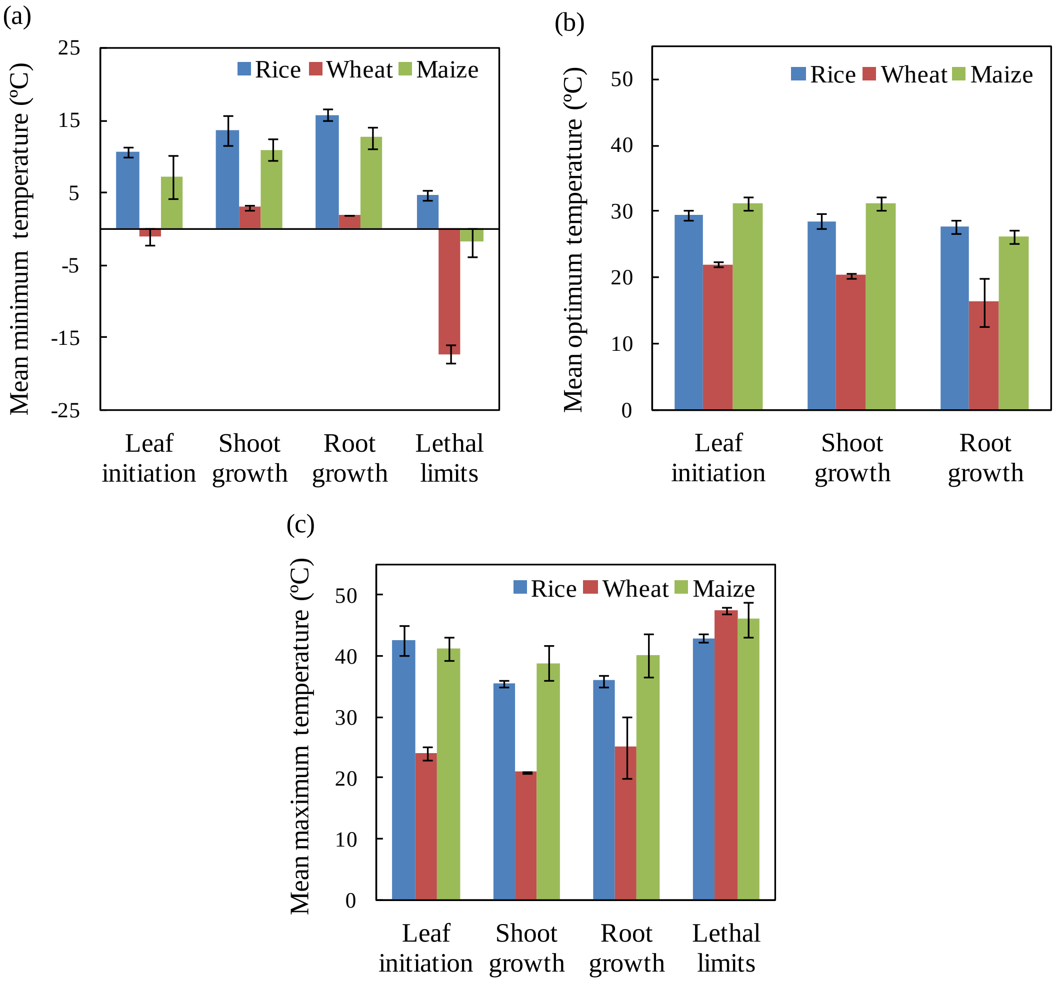

Figure 3.1. Rice, wheat and maize (in separate columns with se). (a) Mean minimum temperature for leaf initiation, shoot growth, root growth, and lethality; (b) Mean optimum temperature for leaf initiation, shoot growth and root growth; (c) Mean maximum temperature for leaf initiation, shoot growth, root growth and lethality

Porter & Gawith (1999) also reviewed temperature sensitivity variations during the course of development. Despite temperature sensitivity for anthesis varies during its course, Tmax seems to be *ca*. 31ºC and Tmin 9.5 ºC (s.e. 0.1 ºC). Exposure to sub- or super-optimal temperatures may reduce grain yields by inducing pollen sterility. Cardinal temperatures are generally highest during grain filling, showing a wider range of cardinal temperatures than for anthesis. Tmax and Topt for grain filling are 35.4ºC (s.e. 2.0 ºC) and 20.7ºC (s.e. 1.4ºC) respectively (Figure 3.2a,b).

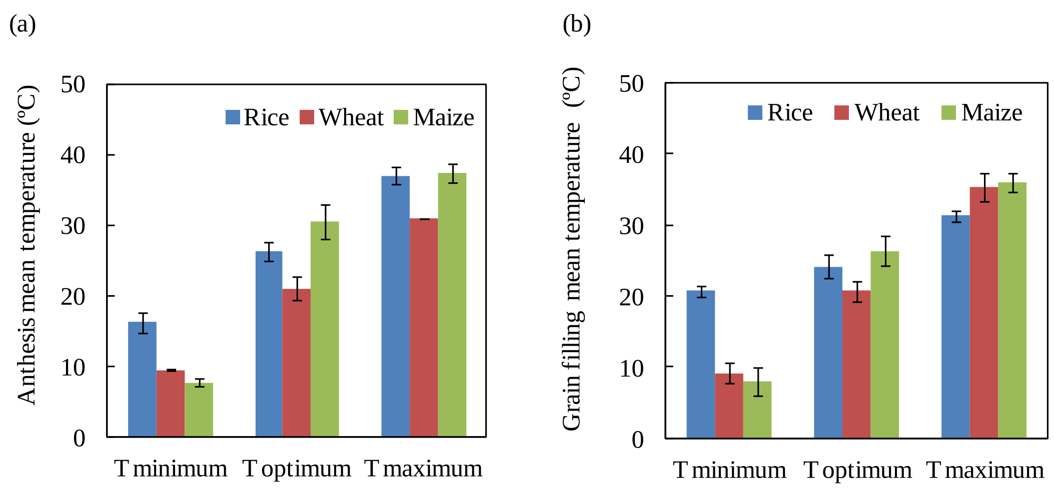

Figure 3.2. Rice, wheat and maize (in separate columns with se). (a) Mean minimum, optimum and maximum temperatures for anthesis; (b) Mean minimum, optimum and maximum temperatures for grain filling

3.4.2 Rice

Table 3.1 summarises the mean lethal and cardinal temperatures for rice (*Oriza sativa* L.) and for their two sub-species (ssp. *japonica* and ssp. *indica*). Mean lethal temperatures are 42.9ºC (s.e. 0.7ºC) for Tmax and 4.7ºC (s.e. 1.3ºC) for Tmin in rice. Above the defined upper and below the lower limit, physiological processes are affected to the extent of causing irreversible tissue damage. The standard error of maximum lethal temperature is small, suggesting that the majority of the development stages during vegetative growth of rice plants are susceptible to heat damage from 40ºC to 45ºC. For instance, at a constant day-night air temperature treatment of 40ºC and under CO_2 enrichment conditions (700ppm), rice plants died during the early vegetative phase (Baker, 2004). Puteh *et al.* (2010) estimated a zero seed germination rate for the rice variety MR73 at 43ºC, based on a linear model. Chaudhary & Ghildyal (1969) found that rice seeds did not germinate under a constant temperature of 43ºC. Livingston & Haasis (1933) and Yoshida (1981) estimated a maximum lethal temperature of 45ºC. At the second-leaf stage and at 45ºC, heat damage appeared in rice seedlings (Han *et al.* 2009). Cells of rice seminal roots stopped division and elongation ceased at 43ºC (Yamakawa & Kishikawa, 1957) and Ehrler & Bernstein (1958) found that at 42ºC root temperature, plants did not survive.

Table 3.1. Summary of mean (±se) of: lethal minimum (TLmin) and lethal maximum (TLmax) temperatures; base (Tmin), optimum (Topt) and maximum (Tmax) temperatures for relevant processes and development phases in rice; n, number of literature sources

Processes		Mean Temperature (±se)(ºC)					
		Specie Oryza Sativa	N	Sub-specie Indica	n	Sub-specie Japonica	n
Lethal Limits	TLmin	4.7 (1.2)	8			2.2 (1.8)	2
	TLmax	42.9 (0.7)	9			42.7 (1.5)	3
Leaf initiation	Tmin	10.7 (0.6)	7	11.8 (0.2)	2	10.5 (0.5)	2
	Topt	29.5 (0.8)	9	29.6 (1.2)	6	29.7 (1.2)	3
	Tmax	42.5 (2.5)	2	40	1		
Shoot growth	Tmin	13.7 (2.1)	4	14.5 (3.0)	2	11.5	1
	Topt	28.5 (1.1)	5	27.5 (0.9)	4	27	1
	Tmax	35.5 (0.5)	2	35.5 (0.5)	2		
Root growth	Tmin	15.8 (0.8)	7	17.5	1	15.5 (3.5)	2
	Topt	27.6 (0.0)	11	26.8 (0.8)	2	26	1
	Tmax	35.9 (0.6)	7	35.5 (0.5)	2	32	1
Phenological phases							
Germination/Emergence	Tmin	11.3 (1.1)	8	7	1	10 (1.7)	4
	Topt	27.9 (2.8)	6	29.9 (4.9)	2	21.7 (2.7)	2
	Tmax	40.1 (1.3)	5	41	1	35	1
Tillering	Tmin	16.4 (0.8)	9	15	1	18.3 (2.1)	3
	Topt	28.4 (1.2)	10	29.7 (2.4)	3	29 (3.1)	3
	Tmax	35.3 (1.1)	6	37.5 (2.5)	2	32	1
Panicle initiation	Tmin	15.8 (0.3)	6	11.4	1	14.9 (1.2)	4
	Topt	26.7 (4.3)	2			26.7 (4.3)	2
	Tmax	33.1 (1.7)	3	33.3	1	33.1 (1.7)	3
Anthesis	Tmin	16.2 (1.5)	8	16.3 (5.8)	2	14 (2)	2
	Topt	26.3 (1.3)	8	28.3 (1.2)	3	24.3 (1.4)	4
	Tmax	37 (1.2)	9	37.7 (1.7)	5	36.9 (2.2)	3
Grain filling	Tmin	20.7 (0.7)	17	21.2 (0.1)	4	17.9 (2.3)	4
	Topt	24.2 (1.7)	7	30	1	21.2 (0.8)	3
	Tmax	31.3 (0.7)	12			29.8	1
Whole plant	Tmin	<13.5 (2.1)	7				
	Topt	27.6 (2.0)	6			28	1
	Tmax	>35.4 (2.0)	7			36	1

The standard error of Tmin lethal temperature is larger than that for Tmax in rice (Figure 3.1a,c), perhaps because, within the same variety, cold tolerance depends on development stage. Between varieties, the ssp. j*aponica* showed a higher cold tolerance with a mean lethal temperature of 2.2ºC (s.e.1.8ºC) for Tmin (Table 3.1). Despite this, rice plants are not able to live below 0ºC. Nishiyama (1976) reported a temperature of 0ºC, at which rice seeds did not germinate and an interval from 2ºC to 5ºC at which seedlings did not grow. Puteh *et al*. (2010) estimated a zero germination rate for the

MR73 variety at a minimum lethal temperature of 0.4ºC, based on a linear model. Chaudhary *et al*. (1969) and Fadzillah *et al*. (1996) observed minimum lethal temperatures around 4ºC for the processes of germination and shoot growth. Lee (1979) recorded the highest percentage of dead seedling of rice plants at the two-leaf stage at a daytime temperature of 10ºC in all his/her (ssp. *japonica x* ssp. *indica*) hybrid lines. Survival rate at this temperature was progressively increased at the four- and six-leaf stages. A higher minimum lethal temperature of around 8ºC has also been found (Hamdani, 1979; Yoshida, 1981) for germination and seedling growth.

The mean cardinal temperatures in Table 3.1 show the temperature tolerances for root and shoot growth, leaf initiation and leaf emergence, and for the most relevant phenological phases and development stages (germination to emergence, tillering, panicle initiation, anthesis and ripening). Topt for root growth is calculated as 27.6ºC (s.e. 1.0ºC) in rice. Ueki (1960) observed damage in the development of grain spikelets as a result of applying water temperatures higher than 32ºC to rice roots of ssp. *japonica* varieties. Mean Tmax for root growth is 35.9ºC (s.e. 0.9ºC) and Tmin is 15.8ºC (s.e. 0.8ºC) in rice. There seems to be a close correspondence between roots and shoot response to cardinal temperatures (Ehrler & Bernstein, 1958; Herath & Ormrod, 1965; Chaudhary & Ghildyal, 1970a). Tmax and Topt for shoot growth are 35.5ºC and 28.5ºC respectively with low standard errors, similar to the results for root growth in rice (Figure 3.1a,b). Tmin for shoot growth is 13.1ºC lower than that for roots, but their standard errors overlap (Figure 3.1a). The response of leaf appearance to temperature is one of the most relevant aspects of cereal development (Gao *et al*. 1992; Ellis *et al*. 1993; Yin & Kropff, 1996). The mean temperature range from a Tmin of 10.7ºC (s.e. 0.6ºC) to a Tmax of 42.5ºC (s.e. 2.5ºC) for leaf initiation, is the widest for all processes except the lethal limits (Figure 3.1a,c). Topt for leaf appearance is 29.5ºC (s.e. 0.8ºC) in rice. Mean cardinal temperatures for root and shoot growth, leaf initiation and leaf emergence showed insignificant differences between ssp. i*ndica* and ssp. *japonica* and the mean cardinal temperatures of the common species *Oryza sativa L.* (Table 3.1).

The phenological phases, defined as the period of time between the stages of rice development, show small differences in optimum temperatures between phases and stages, but wider ranges in minimum and maximum temperatures. Germination of rice seeds has a range in temperature from 11.3 ºC (s.e. 1.1ºC) to 40.1 (s.e. 1.3ºC), making them the highest values we found for Tmin and Tmax for development phases and stages in rice (*Oryza sativa* L.) (Table 3.1). Owen (1971) established that tillering ability (tiller number and leaf number of main stem) is dependent on the management of rice. Oda & Honda (1963) also found differences in tillering temperature response between photoperiod sensitive and insensitive varieties. All mean cardinal temperatures for tillering have standard errors close to 1.0°C in rice and about 2.0ºC in the ssp. j*aponica* and ssp. *indica* (Table 3.1). Both low and high temperatures at panicle initiation increase spikelet sterility, giving a reduction in yields. Spike sterility is higher when a low temperature is applied 5-10 days before heading (Lee, 1979) and may be recognizable by a delay in heading as the panicle continues to develop (Dingkuhn *et al*. 1995). In rice Tmin is 15.8ºC (s.e. 0.3ºC). The highest standard error for Topt (4.3ºC) is for the panicle initiation stage. Tmax was found to be 33.1ºC (s.e. 1.7º).

Rice is most sensitive to temperature during the period immediately preceding anthesis, greatly affecting yields. Enomoto *et al*. (1956) found the germination of pollen in rice in medium fast varieties to be more tolerant to maximum and minimum temperature limits than early and late ones. In the same experiment when comparing Japanese varieties with foreign ones, the minimum cardinal temperature was lower in foreign than in Japanese varieties. The difference between tolerant and susceptible varieties in the temperatures that caused sterility was about 3ºC (Matsui *et al*. 2001). Chilling and mainly heat stress below and above cardinal temperature limits may produce sterility around the anthesis stage. These limits have been established as Tmin of 16.2ºC (s.e. 1.5ºC) and Tmax of 37ºC (s.e. 1.2ºC) for anthesis in rice. Similar limits have been found for the ssp. *indica* and ssp. *japonica*. Sterility is usually associated with poor anther dehiscence, malformation of spikelets, low viability of pollen, decreased number of germinated pollen grains on stigmata or ineffective fertilization (Chaudhary & Ghildyal, 1970b; Satake & Yoshida, 1978; Prasad *et al*. 2006). Ripening or grain filling seems to be the more temperature sensitive stages after anthesis and yields can be greatly affected during this period. Yoshida (1981) concluded that grain weight is affected by temperature during ripening, as well as that grain filling period is shorter under high temperature and the combination of high temperature and low light may seriously affect grain weight and percentage of filled spikelets. Tmin for ripening appears to be the highest value (20.7ºC, s.e. 0.7ºC) compared with other mean minimum temperatures for development processes in rice. Tmax appears to be the lowest value (31.3ºC, s.e. 0.7ºC) compared with other mean maximum temperatures, meaning that the cardinal temperature range for ripening is narrow and standard errors for both temperatures are relatively low (Figure 3.2b). Finally, whole plant cardinal temperatures for development range from Tmin of 13.5ºC (s.e. 2.1ºC) to a Tmax of 35.4ºC (s.e. 2.0ºC) with a Topt of 27.6ºC (s.e. 2.0ºC).

3.4.3 Maize

Table 3.2 summarises the same mean cardinal temperatures for maize as Table 3.1 does for rice and the following results for maize are presented more concisely. The Tmin lethal limit is calculated to be -1.8ºC (s.e. 1.9ºC) and the Tmax lethal limit to be 46ºC (s.e. 2.9ºC). Maize is known to be very susceptible to frost damage, and frost damage is often recorded in temperate growth regions (Crowley, 1998). Carter & Hesterman (1990) found that lethal damage to stem, leaf and ear occurs when temperatures is below -2.2ºC for a few minutes and below 0ºC for more than four hours. There seems to be larger variation in the literature on the upper lethal limit as reflected in the higher s.e. and thus variability (Lehenbauer, 1914; Brooking, 1990). Birch et *al*. (1998b) estimated a temperature of 44ºC and Sinsawat et *al*. (2004) found that temperatures over 45ºC caused irreversible damage to maize plant tissue. However, the same author found that plants grown at a mean temperature of 41ºC were not damaged after being exposed to temperatures of 50ºC. Although there seems to be variation in tolerance to extreme temperatures, maize thrives at temperatures between 28ºC and 32ºC for an entire growth season (Arnold 1974; Yin et *al*. 1995). Tmin on a whole season basis is 6.2ºC (s.e. 1.1ºC) (Olsen et *al*. 1993; Shaykewich, 1994). Tmax is calculated as 42ºC (s.e. 3.3ºC) above which growth stops (Brooking, 1990; Yin et *al*. 1995; Table 3.2).

Table 3.2. Summary of mean (±se) of: lethal minimum (TLmin) and lethal maximum (TLmax) temperatures; base (Tmin), optimum (Topt) and maximum (Tmax) temperatures for relevant processes and development phases in maize; n, number of literature sources

Processes		Mean Temperature (±se)(ºC)	n
Lethal Limits	TLmin	-1.8 (1.9)	8
	TLmax	46.0 (2.9)	6
Leaf Initiation	Tmin	7.3 (3.0)	8
	Topt	31.1 (1.7)	11
	Tmax	41.3 (1.9)	3
Shoot growth	Tmin	10.9 (1.5)	3
	Topt	31.1 (0.8)	3
	Tmax	38.9 (2.8)	4
Root Growth	Tmin	12.6 (1.5)	3
	Topt	26.3 (1.8)	5
	Tmax	40.1 (3.6)	3
Phenological phases			
Sowing to emergence	Tmin	10.0 (2.2)	3
	Topt	29.3 (2.5)	3
	Tmax	40.2 (2.1)	1
Sowing to tassel initiation	Tmin	9.3 (2.7)	12
	Topt	28.3 (3.8)	11
	Tmax	39.2 (0.6)	4
Anthesis	Tmin	7.7 (0.5)	3
	Topt	30.5 (2.5)	3
	Tmax	37.3 (1.3)	4
Grain filling	Tmin	8.0 (2.0)	2
	Topt	26.4 (2.1)	5
	Tmax	36.0 (1.4)	4
Whole plant	Tmin	6.2 (1.1)	9
	Topt	30.8 (1.6)	8
	Tmax	42.0 (3.3)	12

Tmin for root growth was calculated as 12.6ºC (s.e. 1.5ºC). Hund et al. (2008) found a significant decline in root growth in four inbred maize cultivars with a 2ºC decrease in topsoil temperature from 17ºC to 15ºC. Tmax was 40.1ºC (s.e. 3.6ºC) with a Topt of 26.3ºC (s.e. 1.8ºC). As with other stages and phases, the maximum temperature shows a higher standard error, suggesting variability in heat tolerance between cultivars and in experimental design (Figure 3.1c). Mean Tmin was higher for root than for shoot growth (Figure 3.1a), agreeing well with the smaller range as between minimum and maximum temperature for roots than leaves and shoots (Birch et al. 2002; Hund et al. 2008). Table 3.2 shows Topt for shoot elongation to be 31.1ºC (s.e. 0.8ºC). Tmin is 10.9ºC (s.e. 1.5ºC) which is lower than that for root growth and similar to leaf initiation as the two processes to a great extent happen simultaneously (Figure 3.1a). Tmax for shoot elongation is lower than that for root growth at 38.9ºC (s.e. 2.8ºC) (Figure 3.1c).

Tollenaar *et al.* (1979) found Tmin for both leaf appearance and initiation to be 6ºC. However as this experimental design did not include average daily mean temperatures below 10ºC, Tmin is derived from extrapolation of a polynomial fit to the temperature data. A slightly lower Tmin for leaf appearance and initiation was found by Warrington & Kanemasu (1983) as 2ºC and 4ºC where the minima were night temperatures. Mean Tmin for leaf initiation is 7.3ºC (s.e. 3.0ºC). Topt for leaf emergence was found to be from 31ºC to 34ºC (Fournier & Andrieu 1998; Kim et al 2007), with a mean of 31.1ºC (s.e. 1.7ºC) and a Tmax of 41.3ºC (s.e. 1.9ºC).

Cardinal temperatures from sowing to emergence show that Topt is from 26ºC to 33ºC. Tmin ranges from 6ºC to 13ºC and Tmax is approximately 40ºC. Calculated means for Tmin, Topt and Tmax are 10ºC, 29.3ºC and 40.2ºC, respectively with s.e. from 2.1ºC to 2.5ºC. An important period in maize development is from emergence to the end of tassel-initiation as, in this phase, maize goes through its juvenile stage after which some cultivars become long photoperiod sensitive, delaying tassel initiation and anthesis (Birch *et al*. 1998a). Temperature in this phase is important for potential crop yields, since during tassel initiation the potential number of kernels is defined (Tollenaar & Bruulsema, 1988). Heat- or chilling stress during this period can be severe for crop yields. Tmin and Tmax in Table 3.2 for this phase are 9.3ºC (s.e. 2.7ºC) and 39.2ºC (s.e. 0.6ºC), respectively with Topt as 28.3ºC (s.e. 3.8ºC). This indicates that maize is not particularly temperature sensitive during this period compared to other phases. A Topt of *ca*. 28 C° is close to that for other phenological phases and processes during vegetative growth, however the s.e. of Topt (3.8ºC) is the largest standard error for Topt in Table 3.2. This indicates that variation between experiments or more probably cultivars is high. Experimental variation was reported by Ellis *et al*. (1992), who in three experiments with 12 cultivars adapted to tropical, subtropical and temperate climates, found Topt to be between 19ºC and 31ºC.

Maize is particularly sensitive to high and extreme temperatures in the phase before and during anthesis. Especially pollination can be seriously affected by high temperatures. Temperatures over 32ºC reduced the percentage of non-germinated pollen by up to 51% (Schoper *et al*. 1987). Herrero & Johnson (1980) found that maize pollen continuously exposed to 38ºC failed to germinate (Carberry *et al*. 1989) in semiarid tropical conditions. Tmin was found to be 7.7ºC (s.e. 0.5ºC), Topt 30.5ºC (s.e. 2.5ºC) and Tmax 37.3ºC (s.e. 1.3ºC).

Maize kernel yield is affected by high temperatures, which decrease yield and shorten kernel filling, as do low temperatures. Brooking (1993) reported a decrease in kernel filling rate below 13.5 ºC and a linear response between 13ºC and 32ºC. Muchow (1990) and Tollenaar & Bruulsema (1988) both found a growth rate of 0.3 mg kernel/day/ºC from 10ºC to 32ºC. Table 3.2 shows Tmin to be 8.0ºC (s.e. 2.0ºC). Mean Topt is 26.4ºC (s.e. 2.1 ºC) with a mean Tmax of 36.0ºC (s.e. 1.4ºC). Both Topt and Tmax are slightly lower compared to all other stages and phases (Figure 3.2b). As the duration of kernel filling is a major part of the entire growth season of maize, it is thus sensitive to high temperatures for a large part of its developmental cycle.

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3.5 Discussion

The above literature review has identified cardinal temperatures for rice and maize in the same manner as Porter & Gawith (1999) did for wheat, thus now affording the chance to contrast and compare the cardinal temperatures for the three main global cereals (Figure 3.1a,b,c; Figure 3.2a,b). The main conclusions with relevance to climate change are that maximum lethal temperatures are similar for the three crops and range from 43ºC to 48ºC (Figure 3.1c). The highest standard error of a lethal temperature (2.9ºC) is found in maize; this may be because, of the three crops, maize is planted over the widest range of latitude, ranging from c.a. 60^{o}N in Finland and northern Eurasia to 40^{o}S in Australia, Africa and South America. Standard lethal temperature errors for wheat and rice are smaller and close to each other. Minimum lethal temperatures differ in a broad range, showing that wheat has the lowest average minimum (-17.2ºC); maize dies at temperatures just below freezing and rice at temperatures under 5ºC (Figure 3.1a). Again, the largest standard error (1.9ºC) is in maize, but the maize standard error for minimum lethal temperature is lower than that for the maximum lethal temperature.

All threshold temperatures are important for crop development and growth but we wish to highlight a couple that are especially important for yields of the three main global cereals. Maize and rice are very sensitive to the same maximum temperature (*ca*. 37ºC) with similar small standard errors around anthesis (Figure 3.2a); wheat has a lower maximum (*ca*. 32ºC). The reduction in grain set caused by overstepping these thresholds can be dramatic (Wheeler *et al*., 1996a) and all three crops can suffer large yield losses due to sterility at high extreme temperatures. An under-researched topic is the mechanisms by which high temperatures affect pollen meiosis in cereals and plants in general. Reproduction in both animals and plants seems to have rather narrow temperature ranges (Cossins & Bowler, 1987) suggesting a generic research theme relevant to global warming impacts.

Grain filling temperature optima are similar for the three crops and closer than the optimal anthesis temperatures (Figure 3.2b). Maximum grain-filling temperatures are lower for rice than for maize and wheat and are all well-defined. The minimum rice temperature for grain filling is markedly higher than for maize and wheat. The largest temperature response variation appears on the optimum temperature with the higher standard errors for all the crops, although maize also shows a high standard error of minimum temperature.

Caveats for such comparisons are the differences in conditions between experiments identified in the study. It would clearly be desirable to have had all three crops simultaneously monitored under the same controlled environmental conditions, but this was not the case. Differences exist in experimental design, temperature regimes and growth conditions and origins of the varieties studied that may make direct comparison difficult. Details of experiments are provided in the Tables A1.1 to A1.6; (Annex 1). Standard errors of all cardinal temperatures were ca. 8% of mean values for both rice and maize, thus adding confidence to the robustness of the estimates. Another possible source of uncertainty is the degree to which measured temperatures were, in fact, plant and not air temperatures, thus confounding air dryness effects with temperature. Plant canopies can be both warmer and cooler that surrounding conditions. Fischer (2011) shows that air temperatures can be up to several degrees higher than plant (wheat) temperatures following heat shocks but mostly differences are 1-3^{o}C. The mean s.e. of all temperatures found in our reviews are about 2^{o}C; thus within the potential error caused by air-plant differences. In addition, plant temperature thresholds are absolute rather than relative phenomena and if evaporative cooling does not bring plant (or crop) temperature below the threshold then the effects will be the same for air as for plant temperature.

An important point in this and other studies on crop temperature responses is that we are dealing with absolute and not relative thresholds; that is to say moving temperature above a given level induces non-linear responses from plants that are not evident if temperatures remain in the range below or above the threshold. Thresholds do not seem to be defined in terms of a relative change in temperature (ie. a 'delta') but as step changes in plant development and thereby growth. Such threshold responses are not often included in the current suite of statistical and process-based crop models used to analyse and predict the effects of global warming on crop production in different parts of the world. As a result, ensembles of crop models are able to predict mean yields (Rötter *et al.*, 2011) but do less well when predicting yield variability. This infers that the vast majority of currently used yield impact models are likely too optimistic when predicting the effects of warming on food production. This is especially the case for high radiative forcing scenarios leading to land surface warming in excess of 2^{o}C, relative to pre-industrial. Such experiments would be central to defining response functions for extreme temperatures and we suggest a priority would be for events around anthesis and grain filling in the major annual cereals. The standard error data presented in this and the previous paper (Porter & Gawith, 1999) would allow probabilistic modelling of impacts in combination with new scenarios (RCPs) and CMIP5 climate data series. Additionally, integrated experimental studies that include CO_2, drought, nutrients and high levels of warming are needed urgently given the current levels of greenhouse gas emissions (Schellnhuber *et al.*, 2012).

4. Adaptation: Case study of Southern Spain

Publication: Iglesias A, Sánchez B, Garrote L, López I (2015) Towards adaptation to climate change: water for rice in the coastal wetlands of Doñana, Southern Spain. Water Resources Management, 1-25. DOI: 10.1007/s11269-015-0995-x

Objective: To provide potential adaptation options that could improve the water supply reliability and in turn maintain the correct functioning of both the farming system and the natural ecosystem in a Mediterranean region where water resources are limited.

Contribution: B. Sánchez designed the study and coordinated the research team, carried out the interviews and the qualitative analysis and interpreted results between models and public participation.

4.1 Abstract

Rice production in coastal wetlands provides critical ecosystem services that range from flood control to wildlife habitat. In the Iberian Peninsula rice was introduced in the 10th Century. Today Iberian rice accounts for about one quarter of the total rice production of the European Union, almost exclusively cultivated in the coastal wetlands of Spain, with permanent flooding. The intensive water management required to produce rice stands at a crucial point since freshwater supply is deteriorating at an unprecedented rate. Here we explore flexible adaptation options to climate change in the Doñana wetlands - a world heritage and biodiversity site - from two points of view: What are the policy options for agricultural water management in view of climate change? How can informed stakeholders contribute to better adaptation? The first question is addressed by simulating water availability to farmers with the WAAPA model (Garrote et al., 2014) under a range of adaptation policy options derived from the view of the local communities. The second question was addressed by means of participatory research. Adaptation options are framed according to the local environmental, social and policy context. Results suggest that perception on the potential role of new water infrastructure and farming subsidies dominates the view of local communities. The choices of the stakeholders that could be simulated with the

hydrological model, were quantified in terms of additional water availability for the rice farming, therefore providing a quantitative measure to the qualitative solutions. Information provided during the study shaped the final adaptation options developed. Our research contributes to the definition of sustainable rice production in Europe.

Keywords: Coastal wetlands, rice, adaptation, climate change, Doñana, Spain, public participation

4.2 Introduction

The Europe 2020 strategy promotes the development of a greener, more environmentally friendly economy for the European Union countries. The European Environment Agency (EEA, 2012) supports the idea that healthy and resilient coastal ecosystems may provide services needed for this green economy whilst maintaining human wellbeing. However, the challenge remains in defining how to move towards sustainability in practical terms. Coastal wetlands provide a challenging example that combines the economic interests of rice producers, the policy interests of rural development policies, and the environmental interests of water conservation policies.

The Doñana region is a coastal wetland in the Guadalquivir River Basin District of Southern Spain, where water is shared among the natural and the artificial wetland. The recent high temperature and drought episodes are influencing the view of local communities about the need for adaptation in the Doñana natural ecosystems and agricultural systems (De Stephano et al. 2014). The water district is already under environmental pressure (Willaarts et al 2014; EEA 2012), the coastal vulnerability to sea level rise is high (Ramieri et al. 2011; Ojeda et al. 2009), and the potential increase of irrigation demand is very high (Iglesias et al. 2012b).

Drought episodes of the past fifty years in the Sothern Europe aggravate the structural water deficit in the Doñana coastal wetland and the policy strategies undertaken have been capable to deal with extreme situations, but ineffective to solve the conflict among users, especially with the environment (Iglesias et al. 2008a; Iglesias et al., 2008b). Further, the water competition and conflicts will be increased due to a major pressure on freshwater resources as a result of climate change impacts, increased population, pollution problems from agriculture intensification and fragmented and uncoordinated adaptation policy strategies (Iglesias 2009). There is a need of reaching a balance among equity, economic security and the environment by flexible adaptation options that may deal with the increasing pressure on freshwater resources and in turn reduce the conflict among users in the case study region.

The local actors' views need to be considered for designing environmental policies since they may reveal a great deal of helpful information to approach possible adaptation pathways closer to the reality (Picketts et al. 2013). For instance, Sánchez et al. (2014a) found by public consultation that the main drivers to encourage the adoption of new mitigation and adaptation measures by Spanish farmers were pro-environmental concerns, financial incentives and access to technical advice. Furthermore, García-Llorente et al. (2011) found by public consultation in Doñana that the environmental policy strategies should be aimed to increase education programs regarding conservation policies specially addressed to male ageing population with lower education levels.

Several hundred studies have made significant efforts to find climate change adaptation measures (IPCC 2014a) and many in Doñana are contributing to the definition of strategies that can be agreed among the local actors (De Stefano et al. 2014), among the environmental policy design (Martin-Lopez et al., 2011) and among the economic choices (Berbel et al., 2011). This paper aims to address the social and environmental challenges for adaptation of the Doñana coastal wetland. We combine two sources of information to explore flexible adaptation options for the rice farming and the natural ecosystem. First, we define the magnitude of the impacts and the effects of policy by modelling the river basin system. Second, we conduct a participatory data collection process to inform on the social challenge.

The study is organised in five sections. The next Section presents the methods and data; Section 3 provides an estimation of water availability under climate change and the effect of water policy scenarios; Section 4 analyses and discuses adaptation from the view of local communities. Section 5 concludes.

4.3 Methods and data

4.3.1 Study area

The Doñana coastal wetland is recognised of international importance and declared as a Ramsar Wetland, UNESCO World Heritage Site and Biosphere Reserve for being one of the richest natural ecosystems in Europe (García Novo and Marín Cabrera, 2006). The coastal wetland of Doñana is located in the lower part of the Guadalquivir River District (Southern Spain) on the Atlantic coast of Andalusia, the protected area cover an area of over 121,600 hectares under the protection status of Doñana Natural Park and in the eastern side is also located the largest rice (*Oryza sativa L.*) farming area of the country (ca. 36,000 hectares) (Figure 4.1). There are a population of nearly 213,839 inhabitants in the Doñana area, whose activities are mainly addressed to agriculture and tourism and in turn the wetland provides key ecological services such as a stepping-stone in the migration route for birds and waterfowl, a home to many endemic and threatened species, regulation of the local hydrologic cycle and provision of landscape services (Martín-López et al, 2011).

The Guadalquivir River District with around 650 km of length and 57.527 km^2 of area, amounts 7.022 hm^3/year in average of renewable water resources from which 4,007.73 hm^3/year are used mainly for agriculture (87%), domestic use (11%), industrial use (1%) and energy (1%) (CHG 2013). Rice farming is the main source of income for the local population but as well is one of the most water intensive crops of the river basin (De Stefano et al. 2014). Rice farming occupies the 4.2% of the irrigated area and requires over 10,400 m^3/ha/year of water to achieve yields between 9 to 10 t/ha, it accounts a total of 366 hm^3/year, the 14.3% of the annual regulated water resources of the river basin (CHG 2013). The irrigation system for the rice cultivation consist in taking water directly from the Guadalquivir River and flooding the fields until 20 cm of water, depending on the crop needs for each development stage, throughout channels. The semiarid conditions and the salinity of soils make difficult the cultivation of many other crops in the rice area. The flooding irrigation system allows tolerable levels of oxygen, temperature and salinity for growing the rice (maximum concentration of 2g/l of salt in the water) whilst avoids the emergence of a saline crust in the top soil (Aguilar 2010). Further, the sea intrusion increases largely the salinity of the water in the estuary and the Guadalquivir Basin Authority has to provide for dam releases upstream from the rice area to improve the quality of irrigation water.

So far, rice farmers in Doñana received approximately 1,670 €/ha as public subsidies (within the framework of the CAP, Regulation EC/1782/2003) and if they met the integrated production commitment that includes a group of best management practices, they also received 398 €/ha (Regulation EC/1257/1999). Currently, rice farmers will have to meet the measures included into the CAP greening to perceive the equal subsidies. Thus rice production can be considered profitable for farmers since the average cost of producing rice in Doñana is over 1,496 €/ha (reduced due to a highly mechanized agricultural system and higher education training of farm managers that implement precision agricultural methods) and rice price usually ranges between 2,000-2,200 €/ha on average (Aguilar, 2010).

The Doñana coastal wetland is a complex socio-ecological system where the rice production and the wetland ecosystem show a great dependence on water and climate and any change of these factors may alter the state of the environment and local livelihood security.

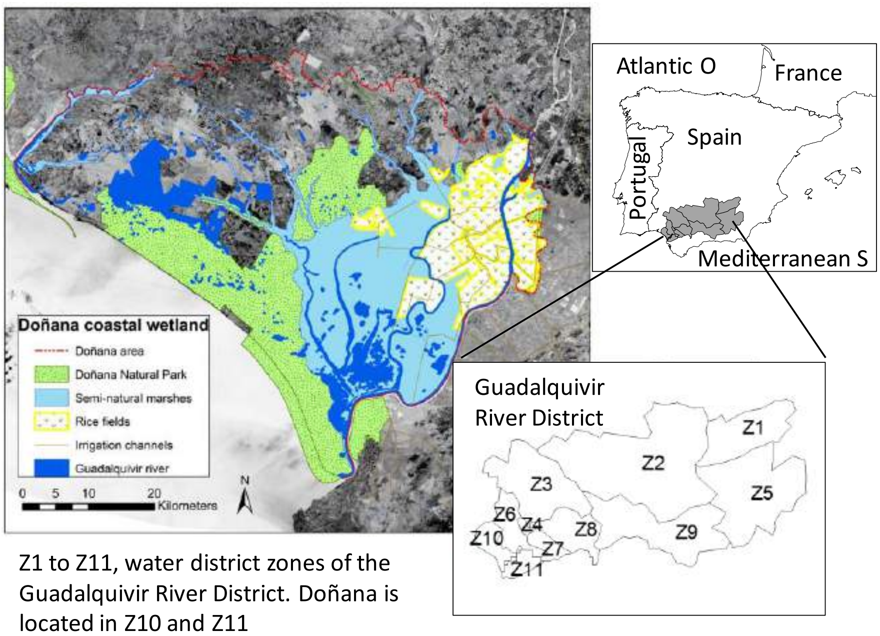

Figure 4.1. Geographical location of the Doñana coastal wetland and the Guadalquivir River Basin District

4.3.2 Framework

Our methodological framework combined two information sources to explore flexible adaptation options for the rice farming and the natural ecosystem in the coastal wetlands of Doñana (Figure 4.2): First, the WAAPA model is used to estimate the effect of exposure to climate change and of different adaptation policy options in water availability, providing information on the environmental challenge. Second, semi-structured interviews and an expert panel, inform on the view of local communities on climate change risk and adaptation measures to rice production and the wetland, providing information on the social challenge.

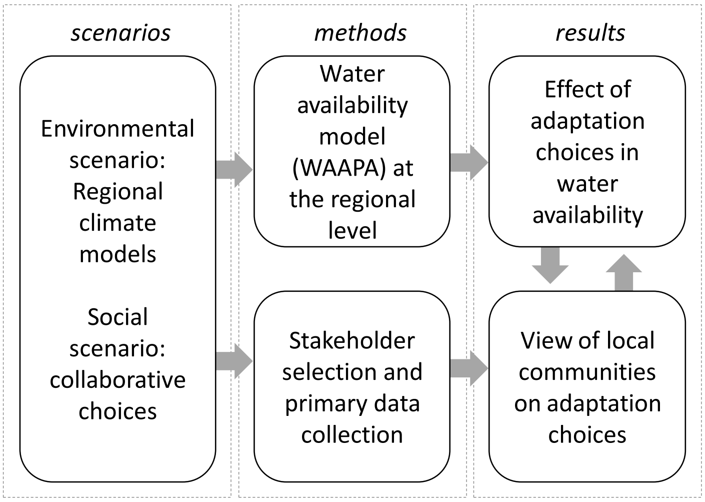

Figure 4.2.Methodological framework

Climate change is clearly defined in the WAAPA model, since it is an input for the simulations. The climate change scenarios for 2071-2010 are explained below. Although these climate scenarios are also presented to the stakeholders, it is inevitable that these scenarios are compared to the perceived current and past water scarcity and climate variability. It is important to notice that water scarcity is a permanent fact in the area and climate scenarios intensify the scarcity level.

4.3.3 Modelling water availability and policy scenarios

The effect of climate change and policy on water availability for irrigation and for the natural ecosystem was estimated with the WAAPA model (Garrote et al., 2011; Garrote et al., 2014). The quantitative analysis provided support for the selection of adaptation policy options that inform local stakeholders.

The WAAPA model (Water Availability and Adaptation Policy Analysis) calculates Maximum Potential Water Withdrawal (MPWW), defined as the maximum water demand that could be provided at a given point in the river network with the available water infrastructure (i.e., reservoirs, dams and water transfers), satisfying management and environmental constraints. MPWW is associated to a given demand type, which implies a minimum required reliability and certain seasonal variation. In all cases urban supply is associated to population and has higher priority than irrigation. Water for ecosystems has also a higher priority than irrigation. The amount of water allocated for ecological flows is defined in each sub-district following the specification of the national regulation on hydrological planning

Model architecture is summarized as follows: (a) Satisfaction of the environmental flow requirement in every reservoir with the available inflow. Environmental flows are passed to downstream reservoirs and added to their inflows. (b) Computation of evaporation in every reservoir and reduction of available storage accordingly. (c) Increment of storage with the remaining inflow, if any. Computation of excess storage (storage above maximum capacity) in every reservoir. (d) Satisfaction of demands ordered by priority, if possible. Use of excess storage first, then available storage starting from higher priority reservoirs. (e) If excess storage remains in any reservoir, computation of uncontrolled spills.

The MPWW analysis was applied to estimate the exposure of the Guadalquivir sub-districts to climate change. The comparison between the MPWW for irrigation in the control and in the climate change scenario provides a proxy variable to estimate exposure to climate change. In this study we consider that urban demand is fixed, because it is linked to population, which in the region under analysis is not expected to change significantly in the next 50 years (OECD 2012a). Water for ecosystems is estimated following the environmental flow requirements specified in the national regulation, which establishes a range between the 5% and 15% quantiles of the marginal distribution of monthly flows in current natural conditions. The central value, 10%, was adopted and it was considered constant. According to climate change projections, this assumption may be perceived as conservative, since streamflow is expected to decrease sharply in the region, but it may underestimate or overestimate future ecosystem water demand depending on future land use and environmental regulations.

Water policy scenarios are constructed aiming to maintain adequate reliability for urban, ecosystem and irrigation demands. The effect of the adaptation effort is estimated from the difference between water availability for irrigation in the control and in the climate change scenario. This is based on the assumption that in the control period irrigation demand is similar to MPWW for irrigation. The assumption is well grounded for the study region, a water scarcity Mediterranean region, where water resources are developed (i.e., infrastructure and management) to satisfy existing demands. The larger the difference between current and future water availabilities for irrigation, the greater the adaptation policy effort required to compensate for climate change though adaptation.

The effect of policy scenarios here is calculated as the increase in future water availability resulting from the implementation of each policy. This study considers four adaptation policy scenarios aiming to reduce the irrigation demand that would be required in the climate change scenario in order to restore the same level of performance that is observed in the control scenario. Demand reduction is not the only policy alternative to reach the objective of adequately supplying the multiple demands of water in the area. In addition to demand reduction, this study considers four adaptation policy measures. Policy option 1 (urban policy) implies to improve urban water use efficiency and reach the target of 175 l/person/day supplied in urban areas. Currently this amount is 300 l/person/day, a value that is considered too high. Concrete examples for implementing this policy could be re-use of urban water or improvement of water technical efficiency within cities (supply management policy), imposed reduction of water per capita use (demand management policy), or water rights exchange programs (supply management policy). The data on urban water use of 300 l/pd is the reference value adopted in the Hydrological Plan of the Guadalquivir River Basin District in time horizon 2015 (taken as "current" scenario) (CHG 2013). The value of 175 l/pd is taken as a target value estimated from the water supply systems in Spain that currently show the smallest per-capita consumption reported (value 195 l/p.d in the Consorcio de Aguas de Tarragona, plus a further 10% increase in efficiency) (CHE 2014).

Adaptation Policy 2 implies a reduction of the environmental flow requirements (from the 10% to 5% quantile of the marginal monthly distribution of runoff). This assumption is clearly challenged within the current strategy for water management, but it is included here to illustrate the trade-off between water for the artificial wetland and for the natural wetland for the discussion among local actors. Adaptation Policy 3 implies to use the storage available in hydro-power dams for regulating water for irrigation. Finally, Adaptation Policy 4 is reached by improving the overall water management of the system by expanding the network of water interconnections and applying water resources systems optimization models.

In this study, climate change scenarios are derived from Regional Climate Models (RCM) driven by two greenhouse gas emission scenarios. The use of RCMs is an important tool for evaluating water management under future climate change scenarios (Varis et al. 2004). Nonetheless, it is well known that the output of the RCMs cannot be used directly if there is no procedure that eliminates the existing bias (Sharma et al. 2007). For this reason, in order to analyse the effect of climate change on water availability for irrigation in a regulated system, here we generate climate change projections based on the bias-corrected runoff alternatives (following Gonzalez-Zeas et al., 2014).

We use two emission scenarios (A1B and E1, to represent the uncertainty derived from greenhouse emissions policies) and two regional climate models to represent the uncertainty derived from model choice). Climate change input for the WAAPA model was monthly time series of streamflow data obtained from the results of the ENSEMBLES project in two climate scenarios (Table 4.1). The transient runs (1950-2100) were split in two periods: control climate (1960-1990, Oct 1961 to Sep 1991) and future climate (2070-2100, Oct 2069 to Sep 2099).

Table 4.1. Climate change scenarios used as input to the WAAPA obtained from the ENSEMBLES project

Scenario name in this study	Global model	Regional model	Resolution and time frame	ENSEMBLES file	Socio economic assumptions (*)
CRNM A1B	ARPEGE	RM5.1	25x25km, 1950-2100	CNRM-RM5.1_SCN_ARPEGE_MM_25km_1950-2100_mrro.nc	A1B
KNMI A1B	ECHAM5-r3	RACMO2	25x25km, 1950-2100	KNMI-RACMO2_A1B_ECHAM5-r3_MM_25km_mrro.nc	A1B

(*) See Nakiçenoviç et al., 2000

4.3.4 Criteria for selecting stakeholders and sample size

Since the mid 1980s there is a growing awareness that the stakeholder may be crucial for effective change and adoption of innovation (Freeman 1984; Eden and Ackermann 1988; Bryson 2004). The fundamental principle is that there are a number of people, organisations and groups, who are critical to the adaptation viability and success. There has been a great deal written in the stakeholder literature on the definition of who or what is a stakeholder. There are numerous definitions of stakeholders; here we consider that stakeholders are groups of individuals with power to directly affect the adaptation future either by supporting or constraining actions (adapting the business definition of Eden and Ackermann (1998) to the adaptation objectives) and recognise that the stakeholders' views will change depending on the specific issue that is being addressed (see Cummings and Doh 2000; Glicken 2000). Following these concepts, we selected stakeholders in two steps: (1) Identification of the groups who have the potential to affect or may be affected by adaptation policies; and (2) Analysis of their power or influence in the adaptation decision in an influence vs interest map (Eden and Ackerman 1998).

Power versus interest grids typically help determine which players' interests and power bases must be taken into account in order to address the problem or issue at hand. As result we grouped the stakeholders in a matrix with four categories (Figure 4.3). First, the critical players are the farmers, since they have high influence and high interest. Second, the context setters are the policy makers, which have high power but lower interest. Third, the significant players are the environmental groups, which have high interest and lower power. Finally, the citizens' group includes the less significant players, with lower interest and lower power. Recognising the importance citizens' opinion for setting values in adaptation, we assumed that the expert scientist group could represent an aggregated view of the population (see below). This assumption is clearly flawed, but may be valid in the absence of data derived from a large survey, that is completely out of the scope of this study. Therefore the views of the expert panel are not formally considered in the study; the reason to include this group in the description is to communicate the research process.

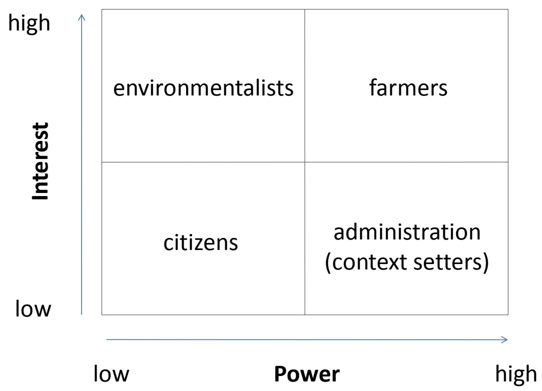

Figure 4.3. Criteria for selecting stakeholder groups, adapted from the theoretical power versus interest grid of Eden and Ackermann (1998)

Once the groups were defined, deciding who should be involved is a key strategic choice. In general, people should be involved if they have information that cannot be gained otherwise, or if their participation is necessary to assure successful implementation of adaptation strategies. These two aspects, together the available volunteer participants, guided the selection of stakeholders for the one-to-one long interviews (see Annex 2).

In all groups, the number of available volunteer participants was very low, limiting the potential sample size. This raises the question of the representation of the sample. In relation to the representation, it is recognised good results can be achieved with just a few interviews, as data become saturated, and data analysis indicates that all themes can reach saturation, meaning additional participants would likely not have added to the depth or breadth of parent responses (Sandelowski 1995; Carlsen and Glenton 2011).

In this study area, the position of the farmers is extremely well defined, since all want to maintain or increase the water supply for rice cultivation. Over 90% of rice farmers in Doñana belong to farmer associations (i.e., Farmer Association body, such as Farmers Advisory Services, Irrigation Communities, Cooperatives or Rice Farming Federations and Unions; see Aguilar 2010). These services include only private members with a technical profile or experienced farmers, and do not include representatives of the local or regional administration. The rice farmer associations provide services to manage irrigation, to the processing of rice after harvest and to facilitate the marketing to the farmers. They also offer technical advice and legislative information, including regular supervision and follow-up of the rice fields and production. The high level of association between rice farmers makes them a strong lobby with very uniform interests. For the interviews we selected members from the five organisations that represent 90% of the farmers, with the aim of providing the representation of the rice farmers in the area as accurate as possible. The Administration body refers to the public service organization which has control on water resources policy, water management and irrigation planning in the Guadalquivir River Basin District. It includes the River Basin Authorities and public officials, with almost absolutely uniform view on the possible solutions facing climate change. The environmentalist body is a lobby group representing the environmental rights and the nature welfare of the Doñana coastal wetland by strategic actions in water management and new regulations; this group has a uniform voice since the 1960s claiming more water for the natural wetland.

4.3.5 Primary data collection

Primary data on observed impacts in the coastal wetland and possible adjustments in view of climate change was collected by means of two qualitative social research methods used in sequence: semi-structured interviews and an expert panel. These are sampling techniques commonly used in policy research (Martín-López et al, 2011; Harrell and Bradley 2009; Ingram and Morris 2007).

Semi-structured interviews were conducted with a standardized guideline to ensure that the researcher covers the material and with an open framework with some discretion about the order in which questions were asked. This sampling method is adequate when the objective is to look deeply into a topic and to understand thoroughly the answers provided (Harrell and Bradley 2009). The interviewer provided information about climate change impacts on water resources in the Guadalquivir River Basin District (included in the Results section) and received information about the observed changes in the coastal wetland and potential adjustments of current water management that affects rice production and the natural ecosystem. In particular, the interview aimed to identify the flexible adaptation measures that could be effective from the social and environmental points of view. A guideline to the interviews was prepared in advance (Annex 2), however the interviews resulted in additional discussion topics that contribute to understand the barriers to implement the potential technical measures.

The semi-structured interviews aim to obtain specific qualitative information about observed climate impacts and possible adjustments from a sample of the population. The main advantage of the method is that it encourages two-way communication, those being interviewed can ask questions to the interviewer, provides arguments for answers, and encourages discussion on sensitive issues. The main limitations are derived from the small sample size and the lack of trust that the interviewed may have about the confidentiality of the responses.

The expert panel assisted in the formalisation of the research questions derived from the semi-structured interviews. The interview survey was conducted during 31 January, 1 and 2 February 2012. To supply a broad outline on observed climate impacts and possible adjustments, eleven key participants from relevant sectors of the coastal wetland were encouraged to give their input (Table 4.2).

Table 4.2. Description of the public consulting conducted in terms of type of consultancy, number of participants and structure of the sample

Type of consultancy	Date and venue	Number of participants	Type of participants
Semi structured individual interviews to local actors	31 January to 2 February, 2012 in Doñana area	11	Farmer Association (5), Administration (3), Environmentalists (3)
Expert panel to experts / scientists	20 April of 2012 in Madrid	3	Research scientists in Hydrology (1), Agriculture (1) and Economics (1)

The requirements for the participants' selection were: i) to be working on activities related to the rice production and the natural ecosystem during the last decade; ii) to have an extensive knowledge about the rice productive sector and to have regular contact with the rice farmers; ii) to have an extensive knowledge about the welfare of the wetland and the natural ecosystem functioning; and iii) to be informed on the water management requirements to cope successfully with the rice production and the natural ecosystem.

The resulting information of the consulting process was also used to inform local stakeholders of the rice farming area by organizing two workshops about the local climate change risk and adaptation with a total of fifty-one participants (De Stefano et al. 2014).

4.3.6 Limitations of the methodology

There are some major limitations of our methodology, derived from the modelling approach and from the consultation process.

The simulations of water availability under climate and policy changes with the WAAPA model have major sources of uncertainty and limitations. The streamflow were derived from the output of regional climate models that include a very crude representation of the hydrological cycle, demands are estimated using globally available data as proxy variables. This is fully explained in Garrote et al. (2015). In addition changes in land use consistent with the climate scenario projections have not been included in the simulations, since the aim was to simulate policy choices for the current wetland system.

A major limitation is derived from the consultation process. Although the three groups of participants selected are reasonably in line with adaptation in the case study, the interview sample is quite small and it is not necessarily representative of all the communities and organizations involved. The study did not address the full range of stakeholders which affect or are affected by climate change adaptation. Here the groups included are likely to have a potential interest and influence in the decision making process of an adaptation strategy, but some actors may be missing due to the limitations in the sample size. A derived shortcoming of the consulting process arises from the current level of conflict between stakeholders having different views on water management. This may have resulted in some degree of mistrust on the confidentiality of their responses. In addition, the consulting process applied in this study only included qualitative information, resulting in difficult comparison among responses and limited in capturing variability among the respondents. The open questions of the semi-structured interviews did not provide enough information for a quantitative analysis. Thus, we identified a portfolio of adaptation options for water resources management rather than seeking consensus on the more cost effective option or priority that could be derived from more quantitative data. Further research is needed in order to incorporate the local knowledge into climate change adaptation local plans and in the wider policy context.

Despite these uncertainties and limitations, the results obtained show a qualitative picture for future water availability in the Guadalquivir basin under a choice of adaptation policy options derived from the consultation. Our findings advance the knowledge of differing climate change strategies at local scale by providing increased comprehension of the stakeholders oppose or support to adaptation options which could be used to incorporate in local adaptation plans.

4.4 Water availability and potential policy choices

Climate change jeopardizes the equilibrium of water resources in the Guadalquivir water district and the impacts will vary as a result of local regulation capacity (Figure 4.4). The difference between runoff and water availability is defined by the effect of storage. Reservoir regulation is one of the most important water resources management policies in water-scarcity areas and has generated significant impacts. Existing reservoirs are being subjected to intense multi-objective demands on limited resources (i.e., water supply, flood control, hydropower, navigation, fish and wild life conservation, recreation, and water quality by assimilating waste effluents).

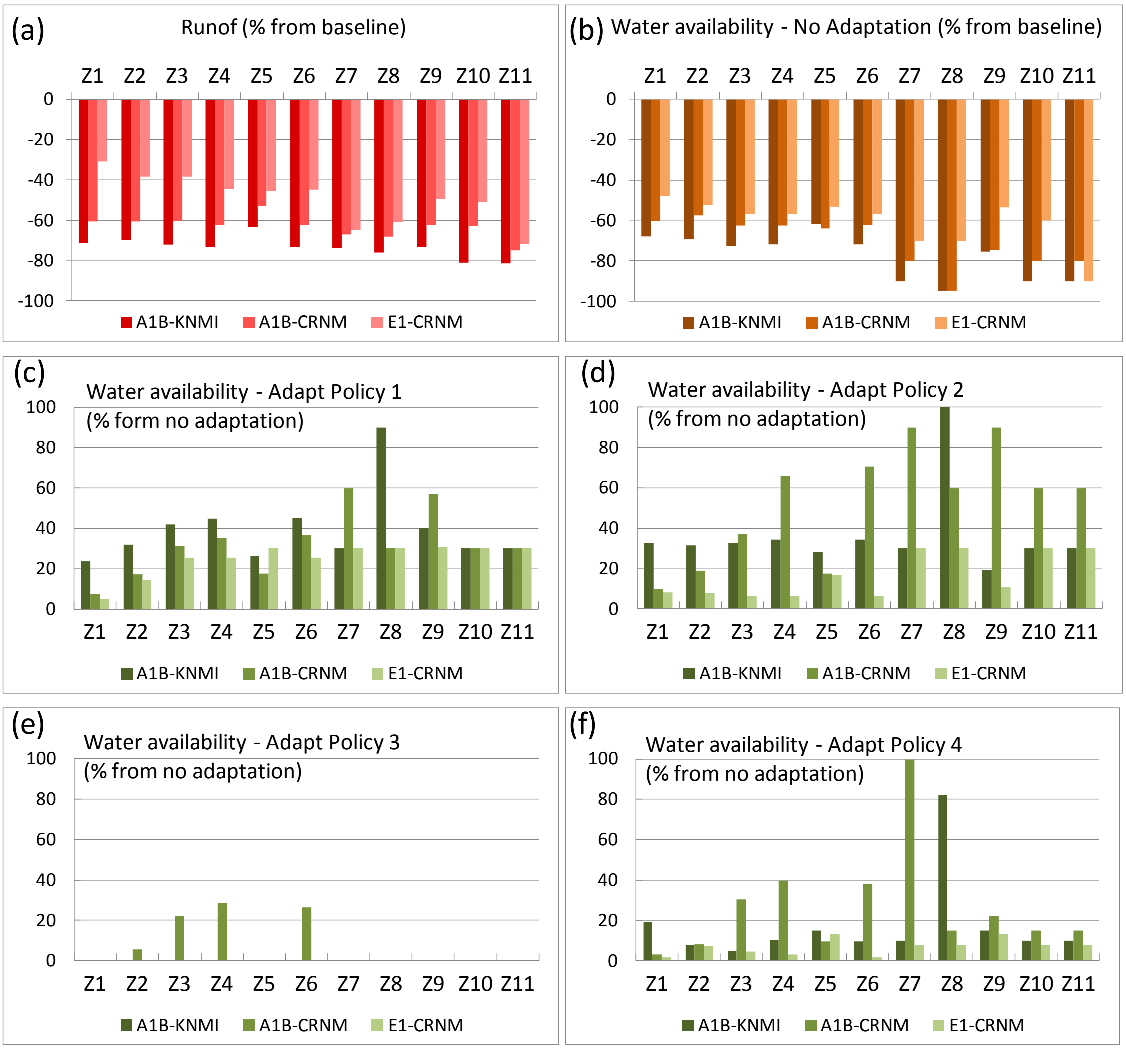

Figure 4.4. Effect of climate change scenario (2070-2100) with respect to control run (1960-1990) for the RCM models forced with two emission scenarios in the Guadalquivir water district. (a) Per unit reduction of runoff; (b) water availability for irrigation with current policy; (c) water availability for irrigation with improved water policy in urban areas; (d) water availability for irrigation with water reduced allocation for environmental uses; (e) water availability for irrigation with hydropower reservoir water conservations; (f) water availability for irrigation with improved the overall water management of the system by water interconnections

These scenarios of water availability (Figure 4.4) demonstrate that in water scarcity regions, water availability is likely to be one of the great future challenges. Defining future water availability under different adaptation policy options is therefore a basic step for water policy formulation.

Reductions of water runoff and increased variability, resulting from exposure to climate change, will lead to significant decreases in the water availability (Figure 4.4). This clearly demands for adaptation policy measures. Here we only consider impositions of demand restrictions since regulatory capacity is already at a maximum in the river district. This is particularly true in the case of irrigation water demand scenarios since it is reasonable to assume that, without changes in policy, land use or technology, projected irrigation demand in the basin will be higher than present irrigation demand even if farmers apply efficient management practices and adjust cropping systems to the new climate. Moreover, when policy and technology remain constant, it has been shown that agricultural water demand will increase in all scenarios in the region (Iglesias et al. 2007, Iglesias 2009). The main drivers of this irrigation demand increase are the decrease in effective rainfall and increase in potential evapotranspiration (due to higher temperature and changes of other meteorological variables).

4.5 The view of local communities: main risks and local adaptation options

Here we present the results of the consulting process (with key local actors and the experts) focusing on a) how the accelerated state of climate change is already affecting the rice production and the natural ecosystem and b) what are the main conflicts and the potential opportunities for societal consensus on local adaptation options.

The results were first generalized into appropriate categories using the topics included in the interview guideline and expanded in Table A2.1 in Annex 2. The categorization was conducted by the primary researcher, and then assessed and verified by other researchers and the experts. Table 4.3 synthesizes the interviews results. The local actors' views fell into the following categories: (1) risks derived from changes in the climate and degree of social concern on them and (2) local adaptation options according to the identified risks. In this second category, we characterise the: current implementation level per adaptation option identified; acceptance (green) or rejection (red) of the local adaptation options by farmers associations; acceptance (green) or rejection (red) of the local adaptation options by environmentalists; and support for (green) or rejection of (red) the local adaptation options from the administration. The white cells make reference to "no opinion" answers.

Table 4.3. Summary of the view of local actors on climate change risks and adaptation options

Risk derived from changes in the climate / Degree of social concern	Local adaptation option	Current implementation level(1)	Acceptability to farmer associations	Acceptability to environmentalists	Support from the administration
	I. Technological measures to face the risk				
Increased water scarcity /High	Water recirculation and reutilization within the paddy rice	M			
	Increase the technical efficiency of the irrigation systems	L			
	Installation of flow meters	L			
	Laser levelling	H			
	Additional water infrastructure	n.a.			
Increased water salinity /High	Water releases from upstream reservoirs	M			
	New pipeline to bring in the water directly upstream from the salt water intrusion	n.a.			
Increased soil salinity /High	Flooding irrigation systems to wash soils	H			
	Organic production (good farming practices)	L			
Increase invasive sp. or pests /Medium	Integrated production (inputs use efficiency)	H			
Decreased rice yield and quality /Low	New longer cycle rice varieties	L			
	New rice varieties adapted to water and heat stress	L			
	II. Organizational measures to face the risk				
All risks /High	Reduction of the available cultivated surface	L			
	Crop diversification and diversification to others activities (e.g. aquaculture, agro-tourism)	L			
	Anticipating local and regional water shortages	L			
	Increase monitoring and information on water use and availability at local level	L			
	Setting of irrigation turns	M			
	III. Governance measures to face the risk				
All risks /High	Actions at the basin level leading flexible adaptation strategies to climate change	L			
	Improve transparency and public participation to encourage agro-environmental awareness	L			
	Increase scientific research, field studies, dissemination	M			
	Improve coordination between institutions, data sharing	L			
	Encourage a long-term perspective in water management	L			
	Implement good practices defined in the WFD	M			
	Increase in farmers training and technical advice	M			
	Supplemental transfer water from the Guadiana new riverbed	n.a.			

(1) L: Low implementation level, M: Medium implementation level, H: High implementation level, n.a. not available

The first category describes stakeholders' perception on the risks derived from changes in the climate and the degree of social concern to them. The results of the interviews suggest that that the major risks in the case study area are water scarcity, salinity problems in water and soils, and to a lesser extent increased invasive species and pests and decreased rice yields and quality. Most respondents' perceptions stemmed from the scarcity of water as the main risk to be concerned. A possible reason why water scarcity is perceived to be the most important risk is the fact that it can easily lead to fall of productivity and rice yield reductions and in turn provoke biodiversity losses. The foresee sea level rise projections in the coastal wetland are expected to worsen the water quality in the lower part of the Guadalquivir River Basin, the case study area, due to larger marine intrusion (IPCC 2014a; Ramieri et al. 2011; Ojeda et al. 2009). An increased relative water scarcity, together with higher levels of salinity, makes rise conflicts and competition among users over the allocation of water (Rijsberman 2006).

The literature review and the findings of this study suggest that higher temperatures are also expected to change water demands and have direct physical effects on the plant growth and development (IPCC 2013, Hanak and Lund 2012). Pulido-Calvo et al. (2012) found that in dry periods a mean temperature increase of 1°C in low altitude locations of the Guadalquivir River Basin will result in a mean increase of 12% in the irrigation demand on outflows. Rice is particularly sensitive to heat stress and may suffer serious damages during the anthesis to maximum temperatures above 37 °C and especially when it is exposed to water stress during the entire flowering stage (Sánchez et al. 2014b). Although the expected mid and long-term scenarios of high temperatures are not recognize as a relevant risk by responses of farmer associations, they are already changing the rice growing calendar and introducing new varieties which are more tolerant to heat stress and longer cycle rice varieties (e.g. J-sendra 155 or Puntal 145).

In a qualitative way, the farmer associations responses reflected that farmers in the Doñana coastal wetland: (i) are likely more concerned about the present than about the future; (ii) are very aware of the damage of current climate extremes in rice production and the natural ecosystem, although they do not entirely recognise that the intensification of current extremes may be a consequence of the climate change; (iii) probably do not perceive increased climate variability as a risk to be concerned in the long-term, since they have a shot-term view more addressed to profit-driven principles than to those related to climate change; and (iv) are likely more concerned about severe droughts or salinity since they have faced these events over the years. Rice farmers have demonstrated to have good adaptation capacities to current and past extreme events, but they do not seem to be particularly open to innovation for the forthcoming risks linked to climate change.

Forming the second category, the respondents provided a broad spectrum of local adaptation options for the rice production to face the identified risk. We organize them into three main groups: technological, organizational and governance measures. The following categories are related to the current implementation level of the options, farmer associations and environmentalists' acceptability and administration support per option.

Different points of views about the adaptation options were stated depending on the type of participants. Almost half of adaptation options included in Table 4.3 confront farmer associations and environmentalists' views, since the options may not be fully corresponding to their own interests and goals. Farmer associations try to promote technological and governance measures that involve options to build new water infrastructures (e.g. a pipeline to bring in the water directly upstream from the salt water intrusion) or increase the water supply to the rice crops (e.g. water releases from upstream reservoirs or supplemental transfer water from the Guadiana new riverbed). So far, environmentalists and administration have null acceptance and support from those options that may result in higher economic costs and environmental impact of new infrastructures. In the perception of the farmer associations, measures that may imply lower yields (organic production, rice varieties adapted to climate change) or reductions of the cultivated area should not be accepted. However, Pulido-Calvo et al. (2012) results supported that the current water deficit in the Guadalquivir River Basin may inevitably lead to reductions in irrigated areas. Environmentalists agree with this projection, but the administration seems not willingness to support the change of management or activity.

Technological measures to increase water efficiency at the field level were most likely to be accepted for both farmer associations and environmentalists. For instance, water recirculation and reutilization within the paddy rice or increased technical efficiency of the irrigation systems. Other technological options that have already proven benefits to the rice production and are widely implemented in the area (laser levelling and integrated production) were also fully supported by the administration. Rice farming in the Doñana wetland is characterized to be a highly mechanized agricultural system with qualified labour that uses precision agricultural methods (Aguilar 2010; De Stefano et al. 2014).

Organizational measures related to water management were positively perceived by the farmer associations and environmentalists. Their responses reflected that there is a lack of local monitoring and information on water availability and use. The provision of accurate, accessible and useful water information at different scales is essential to deal with reductions in water availability (Wei et al. 2011). Reed et al. (2006) reported that including thresholds information about the risks at local scale, even when they are difficult to identify, they can further improve the value of monitoring in managed ecosystems. In the perceptions of the two groups, farmer associations and environmentalists, there is also a need of anticipating management options to local water shortages. Once problems have arisen, reactive management efforts can be more costly than anticipating management to reduce risk by actions to enhance the resilience of the river basin (Palmer et al. 2008). Proactive management efforts may include among others: management plans to the risk of water scarcity at the farm level, on-farm reservoirs, improvements in water use efficiency (Iglesias et al. 2007) and, the establishment of water markets to negotiate water between water users and in turn encouraging the reallocation of water rights to restore freshwater ecosystem health (Garrick et al. 2009; Rey et al. 2014). The high number of “no opinion” answers obtained within the category of “administration support” to technological or organizational options is striking. It suggests to some extent a limited commitment to measures addressed at farm or local scale on this topic. Most of questions concerning to governance options were perceived to be supported by the administration, since it directly fall in their scope of action.

Governance measures included options addressed to improve the coordination between institutions. The critical importance of institutional good governance has been previously established as a requirement for the regional adaptation capacity by preceding research (Berrang-Ford et al. 2014; Hanak and Lund 2012; Iglesias 2009). Increase scientific research, farmer training and technical advice were governance options perceived positively by all the groups. Finally, a lack of confidence in the truth or efficacy of governance measures addressed to climate change strategies and environmental awareness is often referred in the farmer associations' responses. These results prove that climate change and environment can be concepts which are not be easily grasped, and tends to be something that is less tangible to farmers. Experts also pointed out the need of encouraging the farmers' long-term views by climate change advisement and capacity building.

Overall, the results from the consulting process stressed the difficult to find adaptation options which are concurrent for the farmer associations, environmentalists and administration preferences. The spectrum of potential adaptation options in the case study can be represent from two end points, the purely environmental one (eco-centric perspective addressed to reduce impacts on the Guadalquivir River resources and the conservation of natural ecosystems), and the fully agricultural (technocratic perspective addressed to ensure rice yields and productivity) (Figure 4.5).

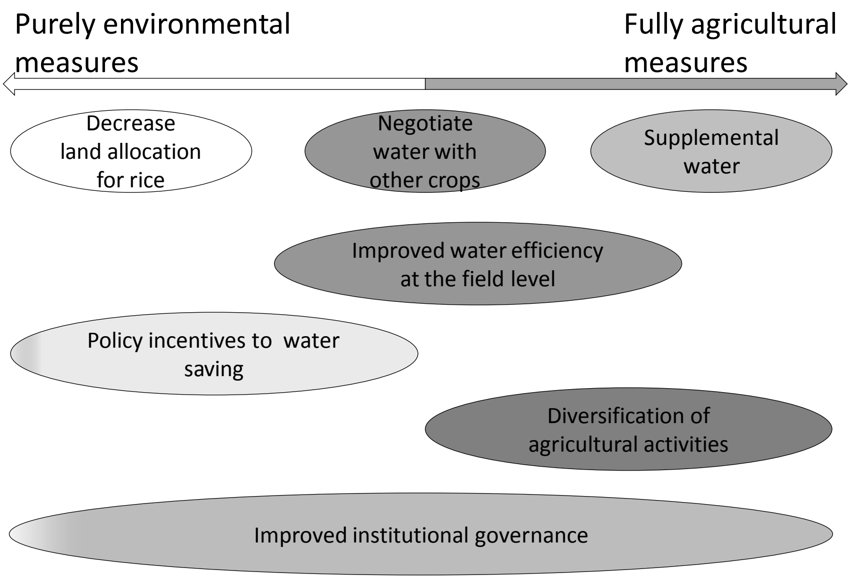

Figure 4.5. The spectrum of potential adaptation options to climate change for the case study

If possible, policy makers and researchers should try to encourage more flexible adaptation options or those located in the middle of the spectrum where environmental and agricultural profit-driven preferences are closer. The international competition in a globalized sector together with the new environmental requirements from CAP might bring more pressure, raising the current conflicts between water users in the area (De

Stefano et al. 2014). The portfolio of adaptation options and initiatives will probably fail if policy makers and advisors do not empower and inform local actors (Jones 2010). Additionally, there is a need of adaptation options that in turn are able to mitigate climate change by having less favourable energy implications (Hanak and Lund 2012).

4.6 Potential policy interventions based on the interrelation of the two results

The interrelation of the qualitative and quantitative components of the study is a challenge. Our approach to interrelation is summarised in Table 4.4 and includes three steps. The first step is the characterisation of water shortages under climate change by the WAAPA model. This diagnostic step is a quantification of the potential water availability changes in the basin and in Doñana, in particular. The broader scale is necessary, since the changes at the local level - and the potential solutions - depend on the changes in the basin. The simulations of water availability changes in all sub-basins range from -45 to -93% of current water availability.

The second step explores the choices of stakeholders. The complete stakeholder views on adaptation measures are a consequence of their recurrent exposure to water limitations under the current climate. The range of options identified includes agronomic, water management, and governance measures. The measures related to water management are then selected to provide an quantitative estimation on their effectiveness with the WAAPA model in the third step.

The approach links perceptions on the potential effect of the measure with quantification by means of a water policy model. We focus on options that presented a high degree of disagreement among the stakeholders groups (Table 4.3). The application of the WAAPA model to these choices helped clarify the objective effect of the options. Furthermore, the WAAPA model was also used to simulate policy options that could be implemented in other sectors, e.g., urban or ecosystems, since these choices could bring a quantitative perspective to compare the local community choices.

The Adaptation Policy 1 addressed to improve water urban use could reach major improvements of water availability for irrigation and in turn avoid reduced water for environmental use by adaptation policy 2. The use of additional water infrastructure for irrigation (e.g. from hydropower reservoirs) was performed by the adaptation policy 3. The simulations showed that the effect for improving water availability of policy 3 was not significant. Adaptation options to improve the water managements by interconnections (a new pipeline connecting upstream water bodies to the rice fields, additional releases from upstream reservoirs or transfer of water) were endorsed into adaptation policy 4. The adoption of policy 4 was specially controversy between stakeholders in their acceptance, however the simulations clearly showed improvement of less than 20% except in a few sub-basins and scenarios.

Table 4.4. Integration of stakeholder choices and potential policy choices

Diagnostic water shortages from model WAAPA and stakeholder views First step	Choices of the stakeholders that can be simulated with WAAPA[1] Second step	Adaptation policy simulated with WAAPA[2] Third step	Quantitative evaluation of the effect on water availability2
Water shortages simulated in all sub-basin ranging between -45 to -93% of current water availability	Flexible actions at the basin levels (trade-offs with environmental and urban efficiency options)	Adaptation policy 1 and Adaptation policy 2	Overall the largest effect on water availability in most of sub-basins and scenarios
	Use of additional water infrastructure for irrigation (hydropower reservoirs to be use also for irrigation)	Adaptation policy 3	Overall no effect for improving water availability except for very small positive effects in for only one climate change scenario
	New pipeline connecting upstream water bodies to the rice fields Additional releases from upstream reservoirs Transfer of water	Adaptation policy 4	Overall improvement of projected impacts less than 20% except in a few sub-basins and scenarios

[1] Included here only the options that can be simulated by WAAPA model, additional information presented in Table 4.3.
[2] Additional information and quantification in all sub-basins presented in Figure 4.4

4.7 Conclusions

Policy is deeply involved in the water sector. Usually, policy development is based on an historical analysis of water demand and supply. It is therefore a challenge to develop policies that respond to an uncertain future. Indeed, science-policy integration is one of the most complex challenges that the scientific and policy making communities face since it involves knowledge sharing and ex-change among a wide range of disciplines and actors (Quevauviller et al. 2005). Despite these challenges, it is possible to achieve this goal and there are success stories throughout the world.

In this study we have attempted to face part of this challenge by presenting an approach that assesses how – water policy and local actors – may influence water in the costal wetland under climate change. Together – policy and stakeholder choices -- may be useful in singling out areas for moving towards adaptation and dialogue. This information may be used to implement and develop policy.

We recognise that the data needs for developing such a decision-making tool are complex and may be hard to satisfy; nevertheless, the conceptual steps that are presented remain valid and may be undertaken at a simplified level. Moreover, since the kinds of policy decisions being considered are at a local level it is likely that the availability of data will be greater.

Qualitative information from participatory research can be of great value in climate change adaptation and policy making when is combined with other tools or models to generate quantitative information (van Aalst et al. 2008). Recent researches have combined both methods to assess and identify climate change risk and adaptation options with valuable results on the adoption of a local adaptation strategy (Picketts et al. 2013; Cohen et al. 2006). Tisdell (2010) evaluated the implications of different water policy options in a semiarid area of Australia by modelling and found that the most cost effective option was a reduction of the water allocation to entitlement holders in order to increase water available for environmental use. Similarly to our study, Cohen et al. (2006) identified, by combining computer-based models and participatory research in the Okanagan Basin (Canada), a portfolio of adaptation options for water resources management rather than seeking consensus on the "best" option or process. Méndez et al. (2012) explored the historical records of the Doñana case study to develop a tailored action research program and provide specific policy-relevant recommendations for water resources management and wetland conservation. They conclude that there is a need of flexible and adaptive institutional regimes, social research and public participation, and improved monitoring and mechanisms for information exchange among others, which seem to be quite concurrent with our findings. Palomo et al. (2011) also carried out a participative process to analyze the current and the future situation in the Doñana wetland. They stressed the scarcity of water as the biggest problem and proposed consensual management strategies that include coordinated local plans and increased professional training. Participatory research can help to advance adaptation planning since knowing and doing is linked through action (Moser and Elkstrom 2011; Picketts et al. 2013).

Climate change is a global challenge with increasing severe consequences at the local level. In the Lower Guadalquivir River Basin District, existing water conflicts between the rice farming and the natural ecosystem are expected to be intensified in the future due to projected scenarios of water availability reduction and higher temperatures. This study aims to identify flexible climate change adaptation options in the Doñana coastal wetlands by simulating water availability to farmers with the WAAPA model and by engaging informed stakeholders in the assessment process. The combination of both methodologies approaches the potential adaptation options to the local environmental, social and policy context.

Results suggest that perception on new water infrastructure and farming subsidies dominates the decision process. Information provided during the study shaped the final adaptation options developed. Our research contributes to the definition of sustainable water management for rice production, livelihood support and the environment.

Results from the consulting process showed how the accelerated state of climate change is already affecting the rice production and the natural ecosystem in the Doñana wetland and what are the main conflicts and agreements on adaptation options under water availability reductions. The water scarcity and the water quality deterioration were perceived by all the informants as the major risks for the good functioning of both the rice farming and the natural ecosystem. Rice farmers do not recognize higher temperatures as a risk to be concerned, but they are already changing the rice growing calendar and introducing new varieties which are more tolerant to heat stress. The rice farming is a highly mechanized and organized agricultural system and rice farmers have a high education level. However, they seem to have a shot-term view of risks and they do not necessarily link them to climate change. Reductions of water availability together with the large water need to irrigate the rice fields and to control the water salinity will raise the current conflict between water users from different economic activities and the natural ecosystem conservation.

There is a shared perception on the need of new and diverse local initiatives to face the increasing water scarcity and salinity risk. The decision making processes of adaptation options is variable according to the stakeholder views. Farmers Association decisions are mainly dominated by technological and profit-driven principles with preference on new water infrastructure and farming subsidies. The lack of generational renewal by the decreasing number of young farmers and the new environmental requirements from CAP can bring more pressure on local farmers' price support. Environmentalists showed reluctance to those options which may result in higher economic costs and environmental impacts due to new infrastructures. Environmentalists and administration actors supported the reduction of rice cultivated area as an effective adaptation option. All the actors and the experts emphasized the important role that could play improved institutional governance and the need of encouraging the farmers' long-term views by climate change advisement and capacity building.

5. Mitigation: Small changes in farming practices

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Objective: To identify the most appropriate agronomic practices under different climate scenarios which result in an optimized balance between crop productivity and mitigation potential and to identify the farmer drivers that influence the adoption of these practices in a semi-arid region in the Mediterranean.

Contribution: B. Sánchez designed the study, coordinated the research team and was the lead author of the paper. She carried out the interviews and the qualitative analysis.

5.1 Abstract

Small changes in agricultural practices have a large potential for reducing greenhouse gas emissions. However, the implementation of such practices at the local level is often limited by a range of barriers. Understanding the barriers is essential for defining effective measures, the actual mitigation potential of the measures, and the policy needs to ensure implementation. Here we evaluate behavioural, cultural, and policy barriers for implementation of mitigation practices at the local level that imply small changes to farmers. The choice of potential mitigation practices relevant to the case study is based on a literature review of previous empirical studies. Two methods that include the stakeholders' involvement (experts and farmers) are undertaken for the prioritization of these potential practices: (a) Multi-criteria analysis (MCA) of the choices of an expert panel and (b) Analysis of barriers to implementation based on a survey of farmers. The MCA considers two future climate scenarios – current climate and a drier and warmer climate scenario. Results suggest that all potential selected practices are suitable for mitigation considering multiple criteria in both scenarios. Nevertheless, if all the barriers for implementation had the same influence, the preferred mitigation practices in the case study would be changes in fertilization management and use of cover crops.

The identification of barriers for the implementation of the practices is based on the econometric analysis of surveys given to farmers. Results show that farmers' environmental concerns, financial incentives and access to technical advice are the main factors that define their barriers to implementation. These results may contribute to develop effective mitigation policy to be included in the 2020 review of the European Union Common Agricultural Policy.

Keywords: Barriers to adoption; Farming practices; Mitigation practices; Multi-criteria Analysis; Surveys

5.2 Introduction

Greenhouse gas (GHG) emissions as a consequence of human activities are causing alterations in the climatic system (IPCC 2007b). The levels of gases in the atmosphere define changes in the climatic systems that in turn define the impact on society and the environment. Responses to face climate change include two kinds of policy intervention: mitigation and adaptation (IPCC 2007c). Mitigation refers to actions that reduce GHG emissions and enhance so called carbon sinks to limit long-term climate change. Mitigation policy is greatly influenced by barriers to behavioural change (Stern 2007; OECD 2012b). Adaptation refers to actions that help society and the environment to adjust to climate change consequences. Adaptation policy actions should not result into GHG emissions increases, and thus must consider their mitigation potential (Klein et al. 2007).

Agriculture is an important source of GHG emissions, contributing approximately 10-12 % of global anthropogenic GHG (c.a. 6.1 Gt of carbon dioxide (CO_2) equivalent (eq) per year in 2005) and accounting for about 47% of methane (CH_4) and about 58% of nitrous oxide (N_2O) (Smith et al. 2007b). On a global scale, the main sources of GHG released from agriculture are: (i) the significant amount of CH_4 mainly from livestock (enteric fermentation) and from rice cultivation (ii) the considerable quantity of N_2O mainly from soils emissions and manure management; and (iii) the CO_2 from decay or burning of plant litter and soil organic matter (Smith et al. 2008; UNFCCC 2008; Snyder et al. 2009).

As a consequence of global mitigation policy, European agriculture has to face new policy objectives derived from the need to reduce GHG emissions. The United Nations Framework Convention on Climate Change (UNFCCC) process recognizes the significant role of agriculture in the global efforts to deal with climate change and to stabilize GHG concentrations in the atmosphere. The commitments and responsibilities agreed by the UNFCCC Kyoto Protocol include the development, dissemination and adoption of mitigation practices that reduce GHG emissions from agriculture (UNFCCC 2008). Loosely speaking, the European Union (EU) shares a collective target to reduce GHG emissions by 20% compared to their 1990 levels by 2020, with different individual targets depending on their emission levels (EEA 2010). The European Trading Scheme (ETS) regulates these emissions but it does not cover the diffuse sectors such as agriculture or transport. The diffuse sectors in the EU are subjected to emissions control measures by the individual Member States' limits for approximately 10% emissions reduction in 2020 compared to the 2005 baseline (Böhringer et al. 2009). Member State GHG emission limits for Spain are 10% by 2020 compared to 2005 GHG emission levels (EC 2009a).

The adoption of agricultural practices for GHG mitigation is a challenge for European farmers and farming advisers (Iglesias et al. 2012b). Although the advisor's knowledge related to sustainable soil management is very comprehensive (Soane et al. 2012), farmers' attitudes and concern about GHG mitigation need further understanding in order to reach standardized practices that meet the new policy objectives (Ingram and Morris 2007). Agricultural management and mitigation practices to reduce greenhouse gases have been widely researched (Smith 2004; Aguilera et al. 2013), but there is a lack of knowledge on what cultural and social factors (such as education, information and traditional local practices, amongst others) and policy incentives have an effect on the implementation of mitigation measures (Prager and Posthumus 2010; OECD 2012b). In conclusion, further research is needed on barriers to adoption of the mitigation practices, effectiveness of mitigation potential of the adopted practices and the influence of climatic trends, economic conditions and farmer's behaviour regarding mitigation practices adoption (Smith et al. 2007b).

The goal of this research is to assess the mitigation practices adopted by farmers at the local level and its relation to farmer specific features. This study addresses crop and soil mitigation measures and livestock is not explicitly considered. It examines the case of

Aragon in Spain, a region with extensive agricultural activity, representing 10% of the Spanish total utilized agricultural area (EUROSTAT 2013). The research provides results on potential agricultural measures for mitigation and the barriers and incentives for their adoption at the local level. We aimed to contribute to policy development and to transfer the information to farmers’ advisory services. To reach this objective, the following three tasks were carried out. First, we reviewed the state of the art of scientific knowledge on GHG mitigation measures in order to select the agricultural practices for our case study based on their mitigation potential. Second, in order to address the suitability of the selected mitigation practices, a prioritization was built based upon consultation with an expert panel and by carrying out a Multi-criteria Analysis (MCA) of their responses under two different climate scenarios. Finally, we tested the implementation of the selected mitigation practices at the local level in the case study area by conducting a wide-survey and we assessed the factors which influence the adoption by farmers of these practices by conducting an econometric analysis.

5.3 Data and methods

5.3.1 Methodological approach

Our methodological approach included three components to build a multi-disciplinary methodology (Figure 5.1):

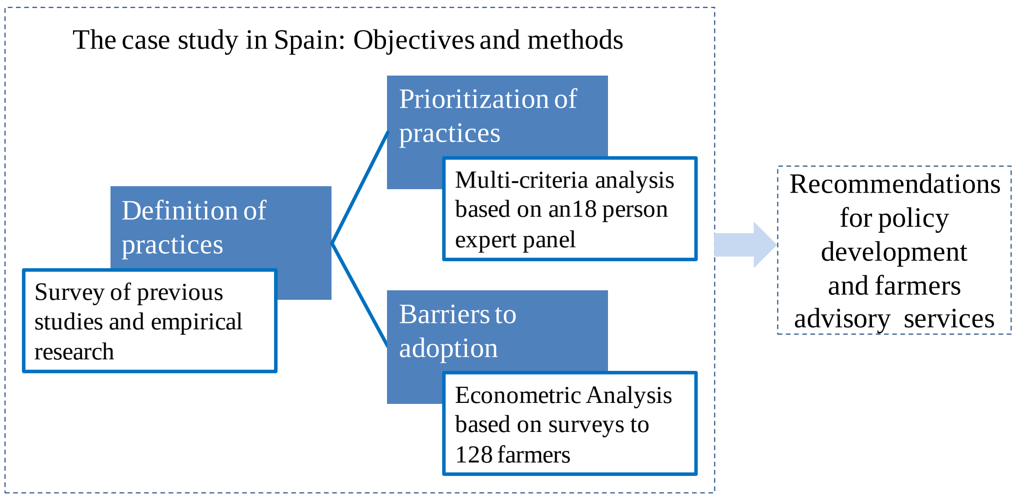

Figure 5.1. Methodology framework used in this study

(1) The mitigation potential of agricultural practices was evaluated by reviewing experimental evidence of soil and crop management practices that reduce GHG emissions. The data collection in our case study area took information from existing publications and studies, analysing the agronomic experimental evidence. The result was a selection of practices that have a greater potential for mitigation.

(2) The suitability of these selected practices was then evaluated by MCA. The data for this evaluation was derived from questionnaires given to an expert panel. The result was a list of the selected practices based on the priorities given to social, economic and environmental factors.

(3) Based on farmers' responses from a survey in the case study region, an econometric analysis was undertaken to estimate the likelihood of adoption of the selected mitigation practices. This probability was calculated as a function of attitudes and farming characteristics of farmers. The result was an analysis of the barriers and incentives for adopting mitigation practices based on the outcome of the model.

The multi-disciplinary methodology accomplished for this research builds an analysis based on the combination of different methods. There is no direct link between the MCA analysis and the econometric modelling methodologies. The MCA serves to evaluate the results of the preliminary literature review on mitigation practices and to identify the most suitable mitigation practices that could be adopted to facilitate the GHG mitigation to expected climate change. The econometric analysis based on surveys to farmers serves to identify the primary mitigation practices already in place in the case study and to assess the different socioeconomic factors that influence the adoption of those measures by farmers. Both methodologies share the stakeholders' involvement (experts and farmers) and they are complementary to approach a mitigation strategy to promote the adoption of suitable practices at the local level.

The results obtained from the analysis provided valuable information that could be used to propose recommendations for mitigation policy development and farmers' advisory services in agriculture under varying climate change scenarios.

5.3.2 Selection of mitigation practices for the case study

The potential of reducing GHG emissions of soil and crop management practices was evaluated by reviewing agronomic experimental evidence. The data collection took information from existing publications and studies. A keyword search was performed in the major scientific databases such as Web of Science, Agris, Agricola and Google Scholar. We collected literature reporting agricultural practices for different geographical areas that show higher mitigation potential. The selection of practices that have a greater mitigation potential in terms of potential soil carbon sequestration rate are shown in Table 5.1 as well as the main sources considered for the selection.

Table 5.1. Detailed description of the six selected mitigation practices for this case study

Mitigation measures considered	Description of the mitigation measure	Potential soil carbon sequestration rate (tCO_2 ha^{-1} year)	Sources
Cover crops in orchard systems	This mitigation measure consists of intercropping spontaneous or human induced cover crops with farmland trees in order to improve soil fertility and water use. It also enhances soil carbon stores thereby increasing the carbon sequestration rate.	0.65 – 1.55	Lal and Bruce 1999; Steenwerth and Belina 2008; Nieto et al. 2013
Reduced tillage / no-tillage	Reducing or avoiding tillage practices, increase soil carbon storage through reducing microbial decomposition, and promoting crop residue incorporation into soil.	0.23 - 0.71	Lal and Kimble 1997; Lal and Bruce 1999; Follet 2001; Ogle et al. 2005; Smith et al. 2008; Álvaro-Fuentes and Cantero-Martínez 2010.
Fertilization with animal manures	Incorporating animal manures to the soil, increases organic carbon stores and enhances carbon return to the soil, thereby encouraging carbon sequestration.	0.1 – 0.33	Paustian et al. 1997; Smith et al. 1997; Follet 2001; Smith et al. 2008 ; Freibauer et al. 2004
Optimized fertilization	Changes in application rates, fertilizer placement or split applications depending on crop needs increases efficiency thus reducing GHG emissions, especially nitrous oxide.	0.36 - 0.62	Lal and Bruce 1999; Follet 2001; Snyder et al. 2009
Crop rotations	Using crop rotations in the same plot, increases soil carbon stores and requires reduced fertilizer use, thereby reducing nitrous oxide emissions.	0.08 – 1.6	Lal and Bruce 1999; Follet 2001; West and Post 2002; Lal 2004
Intercropping	Combining two crops during the same growing season improves soil fertility and soil carbon storage due to more efficient nutrient use and reducing fertilizers application rate as well as GHG emissions.	0.01 – 0.03 (from mulch farming)	Paustian et al. 1997; Lal and Bruce 1999; Lal 1999; Lal 2004; Freibauer et al. 2004

The study of mitigation practices has shown a broad spectrum of options that could apply to the Spanish case study. This spectrum reflects very different and sometimes conflicting views of priorities for adopting mitigation practices according to the variability of mitigation potential driven by different variables such as climate, soil type and/or cropping characteristics. Our case study is the region of Aragon, an intensive agricultural region located in the middle of the Ebro river basin in north-eastern Spain. In Aragón, agricultural activity is located in the central part since the region is bounded by two mountain ranges (i.e., the Pyrenees in the north and the Iberian range in the south). In the central part of the region where agriculture is concentrated, climate and soils are rather homogeneous with a prevailing Mediterranean continental climate and Entisols, Inceptisols and Aridisols as the main soil types (Herrero and Snyder 1997; Ninyerola et al. 2005; Badía 2011). These homogeneous conditions result in a low diversity of agro-ecological settings throughout the main agricultural areas of the region. We have selected the six most important practices according to the agronomic, climate and production factors for our case study.

Detailed below is the MCA of experts' choices that was carried out in order to evaluate and prioritize these selected practices taking into account socio-economic and environmental criteria. The selected practices from the literature review were also included in the surveys with farmers to then assess the barriers to the practices' adoption in the case study area of Aragon. The farmers were also asked for other relevant mitigation measures adopted by them, but there were no significant responses.

5.3.3 Prioritization of practices: Multi-criteria Analysis (MCA) of experts' choices

In order to quantify suitability of the selected mitigation measures, a MCA was undertaken involving the different experts' priorities in order to arrive at an overall score (Georgopoulou et al. 2003; Konidari and Mavrakis 2007; UNFCCC 2011). A supporting tool was used to simultaneously account for the multiple qualitative criteria using the analytical hierarchy process (AHP). The tool is Web-Hipre software (Mustajoki and Hämäläinen 2000; Mustajoki et al. 2004) for decision analytic problem structuring, multi-criteria evaluation and prioritization.

Both 100 to 0 partial value scales and scaling constants were interactively defined based on qualitative value judgments of 18 experts. To supply a broad outline and make the scores robust, experts from different academic sectors of Spain were encouraged to give their input. The weighted sum of the evaluations of every practice over all criteria was computed by the software. The MCA provided composite expert prioritization and a ranking of the practices on the basis of the weighted sum.

The evaluation and prioritization of mitigation choices for the study was based on the results of the literature review of mitigation practices and expert input gathered through a participatory process. A questionnaire was developed and personally implemented with an expert panel in February 2013. The group consisted of eighteen experts from different academic sectors each holding stakes in agriculture mitigation practices to reduce GHG, including representatives from regional and national research institutes and universities. The requirements for the expert selection were: i) the expert performs research work; ii) the expert has been working on issues related to GHG mitigation in agriculture for a minimum of five years; iii) it was desirable that the experts had regular contact with farmers and extensive knowledge of the productive sector; and iv) the experts had sufficient knowledge of the different cropping systems and management to cope successfully with the six selected mitigation practices contained in the survey.

The aim was to gather information on experts’ perception of the six selected mitigation practices in agriculture faced with both a current and a changing climate. To ensure a common understanding by the experts of the criteria and ensure that comparability of the results from the experts' scores, we conducted personal interviews with each of the experts. For the data input collection, the questionnaire was divided into two sections. A complete description of the six selected practices was provided to the experts in the questionnaire (see Annex 3). The experts were advised with examples and guidelines about the criteria’s meaning and how to fill in the questionnaire during the interviews. First, the experts were asked to assign values according to their priorities for the implementation of each mitigation practice on the overall feasibility criteria. The mean values resulted in a ranking of the expert’s priorities for the overall feasibility of the six selected mitigation practices. The implementation was assessed on the farm level. The feasibility was measured in terms of importance for GHG mitigation and desirability for economic, social and environmental farm benefit. The scoring scale for the overall feasibility criteria ranged from 0 to 100, whereby 0 indicated the lowest importance and desirability and 100 indicated the highest. Then the experts were also asked to allocate weights to the evaluation criteria representing their priorities. These criteria were distributed into three main groups: economic, social and environmental. The experts were required to assign weights to the three groups and further to the evaluation criteria within each group. The criteria were measured in terms of importance for GHG mitigation and desirability for economic, social and environmental farm benefit. The scoring scale for the three main groups and for the thirteen criteria within the groups ranged from 0 to 100, whereby 0 indicated the lowest importance and desirability and 100 indicated the highest. Second, the adoption effect of the selected mitigation practices was evaluated by the experts weighting the thirteen criteria under two future scenarios. These scenarios were classified as a current climate scenario with similar climate conditions to those at present and as a climate change scenario with drier and warmer conditions based on the most likely projection according to CEDEX (2011) for Spain (a decrease in average annual rainfall of 8% and an average increase in temperature of 2 degrees Celsius by the 2040s). The scoring scale ranged from -100 to 100, -100 indicated a high negative effect and 100 indicated a high positive effect of the practice for the criteria. The results of the criteria scoring were also weighed to generate an evaluation matrix with practices in rows and criteria in columns, representing the priorities of the experts.

Finally, the analysis of composite expert priorities was computed by the Web-Hipre software including the weighted sum of the evaluations of every practice over all criteria. The analysis of composite expert prioritization provided a prioritization of the practices under the two scenarios on the basis of the weighted sum. The results showed the priority ratios per group of criteria and for every practice considered. The additive value function used to aggregate the component values (Mustajoki and Hämäläinen 2000) is expressed as follows in equation (1):

$$(1)\quad V_j(x) = \sum_{i=1}^{n} w_{ij}\ v_{ij}(x)$$

Where the overall value of the mitigation practice per group of criteria is $V_j(x)$. The group of criteria is *j* (environmental, social or economic), the number of criteria is n and w_{ij} is the weight of criteria *i* of the group *j*. The rating of the mitigation practice x with respect to the criteria *i* of the group *j* is expressed as $v_{ij}(x)$. The weights of the criteria

w_{ij} mean the relative importance of criteria i of the group j changing from its worst level to its best level, compared to the changes in the other criteria (Mustajoki et al. 2004).

The experts' criteria against which the selected mitigation practices were to be evaluated are detailed below (Figure 5.2):

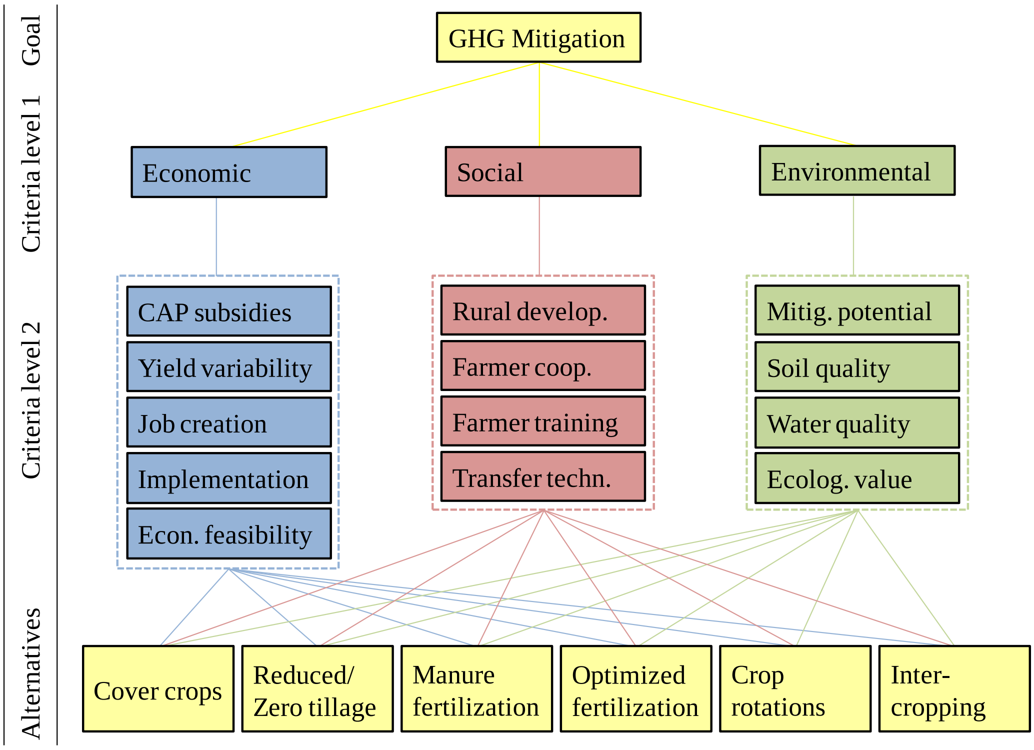

Figure 5.2. Analytical Hierarchy Process diagram of the study. The goal was to select the most suitable mitigation practice from the six considered agricultural practices. Criteria, against which each mitigation practice was measured by the expert panel, were classified into economic, social and environmental criteria

(1) Economic criteria group: CAP subsidies criteria refers to the extent of a practice's dependence on subsidies granted by the Common Agricultural Policy (CAP); the Yield variability criterion evaluates possible changes in crop yields (increases or decreases) implicated by the implementation of the practice; the Job creation criterion assesses the practice's capacity to create more farm employment and thus the promotion of sustainable economies and higher incomes and employment opportunities to the agricultural sector; Implementation criterion evaluates the additional cost of

implementing the practice to the farmer*;* the Economic feasibility criterion evaluates the practice's feasibility in terms of economic profit margin (increases or decreases of net income due to practice adoption).

(2) Social criteria group: the Rural development criterion refers to the extent of the practice's influence on rural development. Rural development criteria is understood as a developmental model for the agricultural sector that corresponds to the needs and expectations of the society at large, and reconfigures rural resources to achieve wider rural development benefits. It must add welfare and high quality conditions to the employment in the agricultural sector to avoid its marginalization (Marsden and Sonnino 2008); the Farmer cooperation criterion assesses the extent to which the practice encourages cooperation between farmers, since the management of some of these practices is often linked to farmer cooperatives and organizations; Farmer training criterion estimates the extent to which the practice promotes a higher level of farmer training, since to be able to implement some of these practices the farmer will have to undergo technical training; the Transfer technology criterion assesses the extent to which the practice contributes to development and transfer technology, since the flow of information between farmers and scientist will rise according to the wider adoption of the practice.

(3) Environmental criteria group: the Mitigation potential criterion assesses the practice's capacity to reduce GHG emissions; the Soil quality criterion estimates the practice's capacity to enhance soil quality; the Water quality criterion estimates the practice's capacity to enhance water quality; the Ecologic value criterion evaluates the additional ecologic value of implementing the practice.

5.3.4 Survey design and data

The study was complemented by a survey conducted in the region of Aragon to assess the farmer's barriers and motivation to adopt mitigation practices by conducting an econometric analysis of farmers' responses. This section of the study examines the case of Aragon, an intensive agricultural region located in the middle of the Ebro river basin in north-eastern Spain. Aragon is the fourth largest region of Spain with 4,770,054 ha and the land is largely dedicated to agriculture with approximately 1,300,763 ha of crop land and 324,354 ha of pasture and grassland (MAGRAMA 2013). The main farming system of the Aragon region is field crops and the main cultivated crops are barley (*Hordeum vulgare* L.) (452,839 ha), wheat (*Triticum aestivum* L.) (284,713 ha), alfalfa (*Medicago sativa* L.) (99,079 ha) and maize (*Zea mays* L.) (63,884 ha) among field crops and olives (*Olea europaea* L.) (59,477 ha) and vineyards (*Vitis vinifera* L.) (37,425 ha) among permanent crops (MAGRAMA 2013). In Aragon, about 25% of the total agricultural land is irrigated. Irrigated areas are mainly located in the centre of the region where water-limiting conditions are present. Annual precipitation ranges from 300 mm in the central part of the region up to 2000 mm in the Pyrenees. However, the majority of the region is within the range 300 - 800 mm of annual precipitation. Air temperatures also vary significantly with mean annual temperatures ranging from 7 ºC to 15 ºC (Ninyerola et al. 2005).

For the main crops grown in Aragon (i.e., barley and wheat in dryland conditions), agricultural management consists in the use of intensive tillage systems to prepare planting, high fertilization rates mainly with mineral fertilizers and frequent use of herbicides to control weeds. According to data from 2012, intensive tillage in Aragon is still frequent; in fact the no-tillage system is currently only implemented by 10% of the area (MAGRAMA 2013). Mineral fertilizers are still the main nitrogen source but organic fertilizers are gaining significance in the area since there is a growing intensive livestock sector in the region (Yagüe and Quílez 2010).

Aragon accounted for 4.8% of total GHG emissions of Spain in 2010 and the agricultural emissions in Aragon were estimated about 3.8 million t CO_2eq, which represents 22% of the total anthropogenic emissions in the region (16.9 million t CO_2eq) (MAGRAMA 2012). Crop cultivation released almost 1.85 million t CO_2eq due to nitrous oxide emissions (N_2O) from crop and soil management. Furthermore, a recent case study identified Aragon as an intensive agricultural area in terms of emissions and accordingly assessed a number of GHG mitigation measures (Kahil and Albiac 2013).

The input data for the econometric analysis were collected via a face to face survey of 128 farmers of Aragon in order to avoid non-response caused by non-contact and generate a greater diversity of answers (Czaja and Blair 2005; De Leeuw 2005). Prior to the survey with the farmers, the questionnaire was tested by a group of qualified respondents to ensure questions were well worded and were relevant to the proper audience. The surveys were conducted at two meeting points for Aragon's farmers, places where the farmers usually go to buy farming supplies or to do paperwork and the selection was made on a "show-up" basis. The surveys were carried out across different days during March 2013. The sample included farmers with holdings covering different areas in Aragon (Figure 5.3), but it is worth noting that this sample is not necessarily representative of the entire region of Aragon.

All farmer respondents were crop producers (100%) and some combine crop production with livestock activity (35%). The majority of the farmers were male (92%) and over 36 years of age (84%). However, only a little over half of the farmers had completed a technical degree (58%) or had received training about the management practices (54%). The proportion of farmers that had received training about the CAP was less than one quarter (23%). In relation to land ownership, 63% of farmers were owners of their farm land, 43% of farmers had more than 100 ha, 24% had between 50 ha to 100 ha, 20% had between 10 to 50 ha and 13% had fewer than 10 ha.

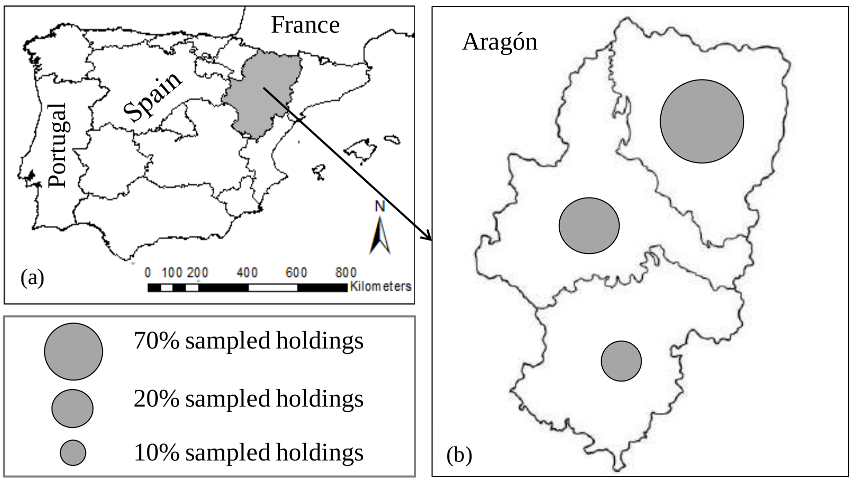

Figure 5.3. Map showing the location and distribution of the sampled holdings. Figure 5.3a shows the Iberian Peninsula with the north-eastern autonomous community of Aragon highlighted. Figure 5.3b further divides the region into its 3 provinces, from north to south, Huesca, Zaragoza and Teruel

The survey was composed of 16 questions in total including check-all and forced-choice questions. In the survey participants were asked questions relating to (i) farmer characteristics such as sex, age or education; (ii) production characteristics such as size of holding, irrigation intensity or type of ownership; (iii) the current adoption of the selected mitigation practices; (iv) institutional factors such as subsidies received and advice; and (v) farmers' concern such as agricultural policy or environmental concern for the adoption of mitigation practices.

5.3.5 Models specification

The adoption of the best agricultural practices is the objective of many economic studies to explore the key determinants of this decision (Prager and Posthumus 2010; OECD 2012b). In each case it is necessary to identify the most appropriate econometric tool in order to measure the influence of cultural, social or economic factors in the adoption decision. The decision making process to assess the adoption of mitigation practices in this study has been divided into two analyses: the intensity of adoption and then the rate of adoption for each individual mitigation practice. Different econometric models have been used in order to determine what are the most relevant factors influencing the mitigation practices adoption in our case study: (i) a logistic Poisson and a Negative Binomial regression which are count data models to determine the factors affecting the adoption intensity (Rahelizatovo and Gillespie 2004; Isgin et al. 2008); and (ii) a logit binomial to determine the relevant factors for each individual mitigation practice (Johnson et al. 2010; Ward et al. 2008).

The Poisson regression model can be considered the starting point for count data analysis. In our case of study, the Poisson model is used to model the number of occurrences of the event of interest and the adoption of the selected mitigation practices is our event of interest (Cameron and Trivedi 2005; Gujarati and Porter 2009). The associated density function is expressed as in the following equation (2).

(2) $f(y_i|x_i) = \frac{e^{-\mu}\mu^y}{y!} \;\; y_i = 1,2, \ldots,$

Where y_i is the adoption intensity of the selected mitigation practices by farmer i and x_i are variables that affect the adoption of these practices. The factorial parameter $y!$ is split as $y! = y * (y-1) * (y-2) * 2 * 1$ whereas the mean parameter or intensity μ_i represents the expected number of events and is expressed as in equation (3).

$$(3)\ \mu_i = E[yi \mid xi] = \exp(X_i'\beta)$$

The Poisson regression model is estimated by maximum likelihood. Some important conclusions are derived from the marginal effect concept, meaning that the change in the conditional mean of *y* when the regressors *x* change by one unit (4).

$$(4)\ \frac{\partial E[y \mid x]}{\partial x}$$

A negative binomial analysis as a statistical test has been carried out to allow an adjustment for the presence of over-under dispersion (variance of y_i greater or lower than its mean value) after running a Poisson regression. Overdispersion might mean that the regression experiences problems with inconsistency, deflated standard errors and grossly inflated t-statistics in the maximum likelihood output.

A binomial logit model was specified to estimate the likelihood that given farmer and production characteristics and farmer behavioural traits would affect the probability of farmers adopting each specific selected mitigation practice. The logistic distribution function represents a generalized form of the model for each dependent variable (5) (Cameron and Trivedi 2005; Gujarati and Porter 2009):

(5) Prob (Farmer i adopts considered mitigation practice) = $P = \frac{e^Z}{1+e^Z}$

Where $Z_i = \beta_1 + \beta_2 * X_i$ and X_i are the logit model independent variables chosen for the regression.

As long as Z_i is between - ∞ to + ∞ the probability the farmer adopts the considered mitigation practices is placed between 0 and 1. As written in Equation (6), the logit model implies that the logarithm of the ratio is linearly related to X_i. Hence, when the logit result is positive, the more the value of the regressor increases and the more likely the value of the regression is closer to one.

(6) $L_i = ln\frac{P_i}{(1-P_i)} = \beta_1 + \beta_2 * X_i + \mu_1$

5.3.6 Variables influencing farmers' decision to adopt mitigation practices

This section discusses variables that are hypothesized to influence the adoption of mitigation practices and are used in the econometric models. While the adoption literature has covered a wide range of causation factors affecting the adoption of best agricultural practices and technology (Rahelizatovo and Gillespie 2004; Johnson et al. 2010; Isgin et al. 2008; Ward et al. 2008), there is limited research investigating the specific determinants affecting adoption of mitigation and adaptation practices to climate change (Cary et al. 2001, Prager and Posthumus 2010; OECD 2012b; Tambo and Abdoulaye 2012; Archie 2013). The explanatory variables used in this study to explain adoption decision are based on both the theoretical and empirical literature of agricultural practices adoption. The implementation of new practices is closely related to innovation or implementing a new idea (Feder and Umali 1993). For example, age and education are essential determinants to innovation (Kivlin and Filegel 1966) and to agricultural innovation (Feder and Umali 1993; Sundind and Ziberman 2001). At the same time, there is considerable literature on attitudes of the public towards environmental commitment and climate change (Eurobarometer Survey on Climate Change 2011) and on people's support for climate change policies (Bryan et al. 2009; Garcia de Jalon et al. 2013; Hanemann et al. 2011). This broad range of studies support the idea that implementation of new choices is determined by a common set of individual characteristics. Therefore here we have selected a set of factors that are closely related to innovation and environmental commitment. The explanatory variables fall under four categories: farmer characteristics, production characteristics, institutional factors and farmers' concerns. Table 5.2 summarizes the descriptive statistics of the variables in the empirical models.

Table 5.2. Statistical summary of dependent variables for the Poisson (Mitigatpractices), the negative binomial (Mitigatpractices) and the logit binomial models (Covercrops, Notillage, Animalmanures, Optifertilization, Croprotations and Intercropping). The Independent variables are common across all models

Category/Variable	Description	Mean	SD
Dependant variable			
Covercrops	Practice is implemented (1 = yes, 0 = no or not sure)	0.21	0.41
Notillage	Practice is implemented (1 = yes, 0 = no or not sure)	0.63	0.48
Animalmanures	Practice is implemented (1 = yes, 0 = no or not sure)	0.50	0.50
Optifertilization	Practice is implemented (1 = yes, 0 = no or not sure)	0.46	0.50
Croprotations	Practice is implemented (1 = yes, 0 = no or not sure)	0.68	0.46
Intercropping	Practice is implemented (1 = yes, 0 = no or not sure)	0.31	0.46
Mitigatpractices	Adoption intensity of mitigation practices (taking on values from 0 to 6)	2.82	1.75
Independent Variable			
Age	Age of farmer in years (1 = less than 35, 0 = 36 or more)	0.15	0.36
Education	Farmer having a technical education (1 = technical degree, 0 = no technical degree)	0.57	0.49
Landowner	Farmer being owner of the farm land (1 = yes, 0 = no)	0.92	0.25
Size	Size of farm in hectares (1 = size< 10 ha, 2 = 10-50 ha, 3 = 50-100 ha, 4 = size>100 ha)	2.97	1.06
Irrigation	Irrigation intensity (1 = low or non-irrigated land, 2 = medium, 3 = high)	1.96	0.57
Subsidies	Farm subsidy received by implementing mitigation practices (1 = yes, 0 = no or not sure)	0.19	0.39
Techadvice	Advice received about the mitigation practices management (1 = yes, 0 = no or not sure)	0.53	0.50
Pacadvice	Advice received about the Common Agricultural Policy (1 = yes, 0 = no or not sure)	0.22	0.42
Awareness1	Agricultural policy concern for the adoption of mitigation practices (1 = yes, 0 = no or not sure)	0.67	0.46
Awareness2	Environmental concern for the adoption of mitigation practices (1 = yes, 0 = no or not sure)	0.54	0.49

SD is standard deviation. Total number of observations = 128

The different factors of mitigation practices adoption may explain more or less effectively the adoption decision facing the farmer. The adoption of mitigation practices varies according to several technical requirements (e.g. machinery, agro-chemicals, fertilisers, seeds), economic requirements (e.g. labour, investment) and consequently results in different risks levels for the farmer. Therefore the factors that influence the range of practices that the study considers are expected to vary among practices. For example, the importance of subsidies varies among practices and so does the additional level of private investment. Education may be linked to technical knowledge required for implementation. The adoption and the hypothesized explanatory variables were assumed to have a log-linear relationship, the adoption in the logarithmic form and the explanatory variables in the linear form, according to the following studies. We consider the age and education of the farmers which has been known to influence the decision to adopt mitigation practices (Johnson et al. 2010; Rahelizatovo and Gillespie 2004; Isgin et al. 2008; Ward et al. 2008; Tambo and Abdoulaye 2012; Archie 2013). The ownership of land (Landowner) was also supposed to have a noteworthy effect on the farmer's willingness to implement mitigation practices (Prager and Posthumus 2010; Knowler and Bradshaw 2007). Based on previous studies, the farm *size* in hectares of cropped land was considered a significant factor influencing the adoption of mitigation measures (Norris and Batie 1987; Knowler and Bradshaw 2007; Isgin et al. 2008; Tambo and Abdoulaye 2012). Furthermore we looked at the irrigation intensity, known to play an important role in the farm production, and hence was assumed to have a significant influence on the decision to adopt mitigation practices or not. Financial incentives (Subsidies) were presumed to be highly significant determinants of adoption decisions also.

Techadvice and Pacadvice were also considered as influential factors representing respectively levels of technical and policy advice received regarding training and information about new practices and changes in related agricultural policy. Prager and Posthumus (2010) pointed out that concern and knowledge of agricultural policy and legislation represents a significant determinant to encourage attitude change (Awareness1). Literature reviewed also showed the importance of having environmental motivation or climate change awareness (Awareness2) to increase the adoption of mitigation practices (Morris and Potter 1995; Prokopy et al. 2008; Tambo and Abdoulaye 2012).

In summary, all our variables were hypothesized to influence the probability of a farmer adopting the mitigation practices under consideration. They were also hypothesized to have a positive impact on adoption decisions, except the *age* of the farmers which was hypothesized to have a negative effect.

5.4 Results and discussion

5.4.1 Expert priorities of mitigation practices

The participatory process (expert's panel and questionnaire) provided a ranking of the feasibility for the implementation of the selected mitigation practices (Figure 5.4). The percentages were distributed as follows: intercropping (67%), crop rotations (64%), fertilization with animal manures (62%), zero/reduced tillage (61%), optimized fertilization (55%) and cover crops in orchard systems (41%). Most of the practices showed similar percentages except that of cover crops in orchard systems. The fact that this practice was less favoured by the experts may be related to the relatively small area dedicated to permanent crops compared with cereals (34% vs. 66% out of Spain). It may further be influenced by the current extent of knowledge on cover crops in orchard systems compared with the other practices proposed which have been more extensively studied and more widely understood in Spain (MAGRAMA 2013).

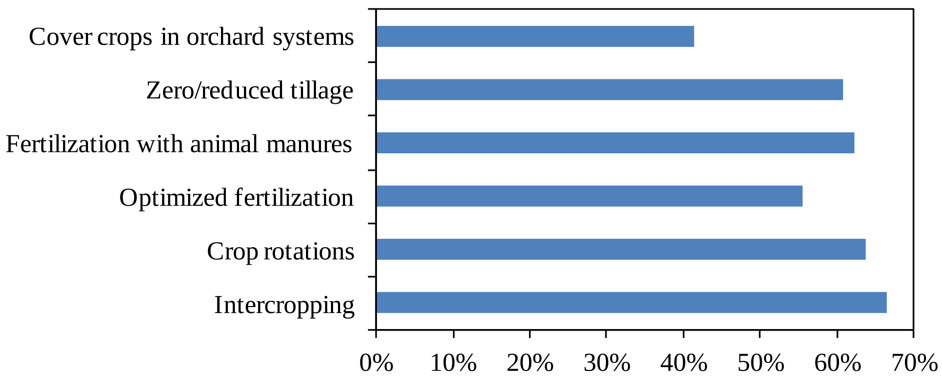

Figure 5.4. Feasibility of the selected mitigation practices according to the expert panel and questionnaire results based on qualitative value judgments of experts

Thus, the experts chose intercropping and crop rotation as their preferred practices in terms of their feasibility potential. This may be due to the similarity between intercropping and crop rotations in terms of management requirements and benefits achieved in GHG mitigation. They are agricultural practices that may be implemented immediately and help to mitigate GHG emissions with relatively low-cost and no major technological requirements. The multiple benefits associated with the adoption of these two practices have generated widespread social acceptance and scientific consensus. West and Post (2002) analysed a global database of 67 long term experiments and reported that enhancing crop rotation may sequestrate an average 20±12 g m^{-2} yr^{-1} of soil organic carbon (SOC). Lal (2004) reported positive effects from rotations based on appropriate cover crops or pastures for enhancing SOC concentration. Other studies (Lal and Bruce 1999; Paustian et al. 1997; Lal 2004) found that benefits on SOC increases and C sequestration may be accentuated when using intercropping due to more efficient nutrient use and reducing fertilizers application rate.

The allocation of the criteria weights was determined by the experts' priorities of the three main groups: environmental, economic and social. These were distributed as 44%, 35% and 21% respectively. Within the environmental group, the most valued criteria were the mitigation potential criterion and the soil quality criterion (Table 5.3).

Table 5.3. The allocation of weights to the relative importance of criteria and sub-criteria by the expert judgment

Criteria weights		Sub-Criteria weights	
Economic	35	CAP subsidies	64
		Yield variability	81
		Job creation	72
		Implementation cost	77
		Economic feasibility	83
Social	21	Rural development	74
		Farmer cooper. level	63
		Farmer training level	74
		Transfer technology	72
Environmental	44	Mitigation potential	90
		Soil quality	87
		Water quality	86
		Ecologic value	79

The results of the analysis of expert composite priorities (Figure 5.5) showed similar trends between experts' priorities for both the current climate and the climate change scenario. Experts showed greater acceptance of practices such as optimized fertilization and cover crops and minor acceptance in the practice of fertilization with animal manures according to this analysis.

For both climate scenarios considered, mitigation practices that showed higher scores for most of the criteria were optimized fertilization and cover crops reflecting a greater positive effect on GHG mitigation by implementing them. Optimized fertilization stood out for its capacity to enhance water quality and the extent to which the practice's adoption would contribute to develop and transfer technology (Smith et al. 2007a; Snyder et al. 2009). Moreover, it has been observed that when fertilizer was used more efficiently soil C sequestration is enhanced (Follet, 2001). In relation with the capacity of cover crops in orchard systems, it was also noted the capability to enhance both soil quality and the additional ecologic value for implementing the practice. Improvements in the soil organic matter content, microbial biomass C, and the microbiological function have been reported under this practice (Steenwerth and Belina 2008). Thus, the potential for C sequestration with this practice is significant and noteworthy particularly in Mediterranean agroecosystems (Nieto et al. 2013).

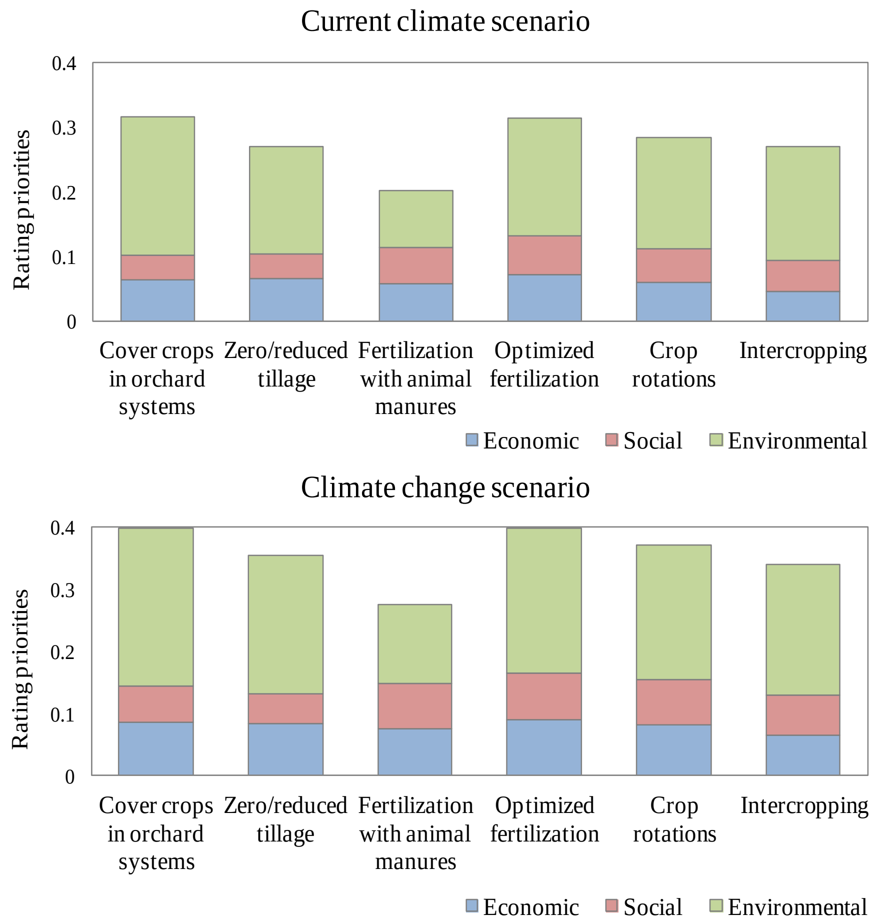

Figure 5.5. Analysis of composite priorities of the selected mitigation practices under different scenarios by expert criteria

The MCA analysis under current climate scenario also showed a negative effect of the capacity of zero tillage to create more farm employment, since the adoption of this practice may reduce the labour needs. The adoption of reduced/ no-tillage practice has been widely highlighted for their mitigation potential (Lal and Kimble 1997; Lal and Bruce 1999; Follet 2001; Ogle et al. 2005; Álvaro-Fuentes and Cantero-Martínez 2010). The success of the practice has been associated with the advance in weed control methods and farm machinery (Smith et al. 2008) thus reducing the need for manual labour. Besides, the adoption of reduced/ no-tillage practice showed high benefits on the soil quality and low costs of implementation for the farmers. Concurrently, the MCA analysis under current climate scenario showed a negative effect of fertilization with animal manure on the additional cost of implementing the practice and on water quality. Fertilization with animal manures demands large management requirements such as improved storage and handling and it could have adverse effects due to higher costs (Smith et al. 2007a). In addition the cost associated with the application of the animal manure in the field (labour and fuel) can make fertilization with animal manure a more expensive practice than mineral fertilization. The MCA analysis also highlighted the beneficial effect of fertilization with animal manure on its capacity to enhance soil quality and crop yields, as well as the extent to which the adoption of this practice would contribute to develop and transfer technology. However, this practice should be taken with caution since despite there is a positive mitigating effect of applying fertilization with animal manures on reducing CO_2 emissions, there could be increases on N_2O emissions and negative effects on water quality (Smith et al. 2008).

For the climate change scenario, under a drier, warmer climate the need for these practices will be greatly increased, hence the reluctance to adopt them will be diminished and the relative benefits associated with their implementation more pronounced (Álvaro-Fuentes and Paustian 2011; Iglesias et al. 2012a; Aguilera et al. 2013). Although all scores increased, adoption of optimized fertilization and cover crops still had the greatest positive effect. The negative effect of implementation cost and water quality was reduced for fertilization with animal manure, which although beneficial under current climate conditions, will be more worthwhile under the climate change as predicted and so it will be the investment in this change of practice. The dual role of some of these practices in mitigation and adaptation reinforces the need for adoption under the climate change scenario, as is the case of the direct seeding/reduced tillage practice which encourages the retention of water soil content whilst reducing GHG emissions.

We have synthesised results in a simple qualitative ratio of the effort (level of costs to farmers) to benefit (potential mitigation benefit) of the different mitigation measures listed in Table 5.1. Based on the expert responses under the two scenarios, cost marks were assigned 1, 2, 3 and 4 values for the calculation. Figure 5.6 summarizes the effort to benefit ratio (y axis) for the mitigation measures (x axis). In general, measures that present a higher effort to benefit ratio, also show a higher level of uncertainty, such as the case of the measures for reduced tillage and fertilization with animal manures. The measures that are more widely accepted by experts have a relatively low effort to benefit ratio, but in contrast they show less uncertainty, suggesting that synergies decrease the uncertainty.

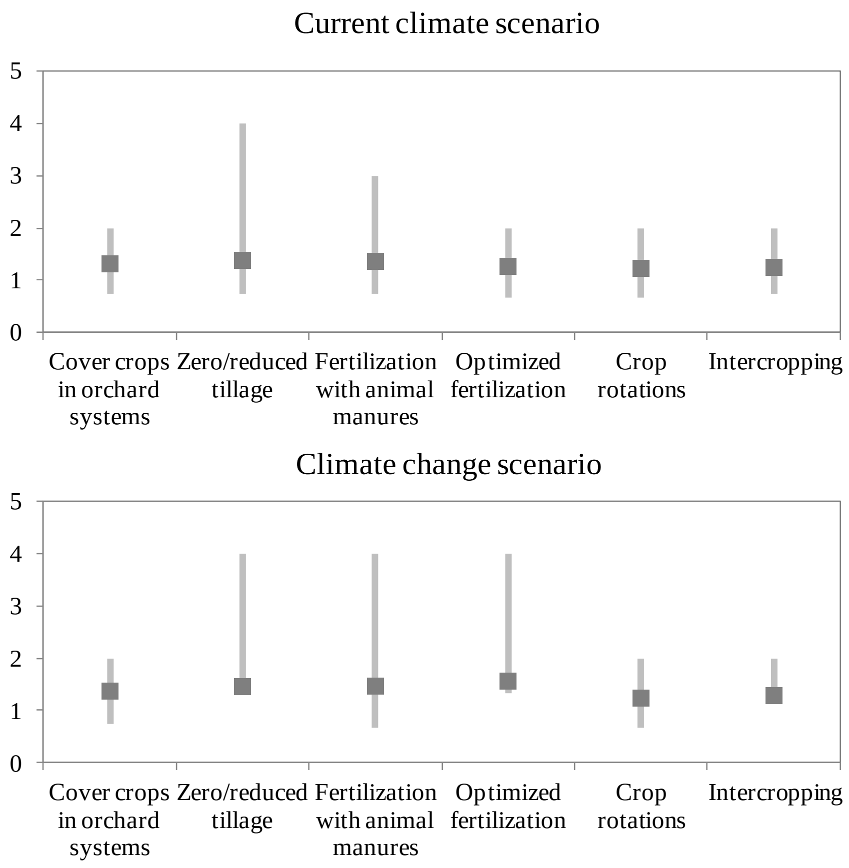

Figure 5.6. Effort to benefit ratio for the six selected mitigation measures

5.4.2 Farmers' response to adopt mitigation practices

Recent studies have focused their interest on the wider range of motivations for farmers' decisions that can improve the adoption of agricultural practices with significant mitigation potential of GHG emissions (Cary et al. 2001; OECD 2012b). Since financial incentives, education, information and production characteristics influence the outcome of policy incentives, more attention needs to be paid to the knowledge on how these factors influence the adoption of mitigation practices at local level to facilitate the work of European policy makers (Prager and Posthumus 2010).

Level of mitigation practices adoption

The percentages of sampled farmers adopting each of the mitigation practices considered for the analysis are detailed in Table 5.4. The most frequently adopted practice was crop rotation, with an adoption rate close to 69%. This could be accounted for by the fact that the farmers of Aragon are aware that by rotating they can achieve higher benefits since this practice is economically motivated. The high adoption rate of crop rotation can be also explained by the widespread modernization of irrigation systems in field crops of Aragon (Lecina et al. 2010), because the farmers with modern sprinkler systems are more willing to rotate two crops per year (winter crop - cereal or leguminous and summer crop - maize) in order to obtain higher crop yields. There are also areas where alfalfa is widely grown for 4-5 years, which involves rotation of different crops at the end of this period for a similar time.

Table 5.4. Adoption rates of mitigation practices by farmers sampled in Aragon

Mitigation practice	Numbers adopted	Percentage adopted
A1.Cover crops in orchard systems	28	21.9
A2.Reduced tillage / no-tillage	81	63.3
A3.Fertilization with animal manures	65	50.8
A4.Optimized fertilization	59	46.1
A5.Crop rotations	88	68.8
A6.Intercropping	40	31.3

Reduced tillage / no tillage and fertilization with animal manures were relatively frequently used mitigation practices, being adopted at rates of approximately 63% and 51% respectively. The practice of reduced tillage/no tillage is seemingly quite well promoted in the region by local cooperatives, agricultural associations, agricultural unions and research groups given its numerous benefits to both farmers productivity and environmental sustainability. In fact, Aragon is the second autonomous community of Spain with the largest adoption rate of direct seeding; representing 18.5% of the Spanish total (MAGRAMA 2013). The relative swiftness of its implementation coupled with support and advice from external groups has contributed to this being a favoured option of many farmers. With regard to the application of animal manure, it is worth noting that 35% of the farmers questioned combine both crop cultivation and livestock farming and thus the use of animal manure as fertilizer amongst these farmers and their neighbours is relatively prevalent. However in order for the practice to become more widespread, the manure must be available in sufficient quantities and at the appropriate moment and the application time and cost would have to be reduced significantly, otherwise it does not represent a worthwhile investment for the farmers concerned.

Mitigation practices with adoption rates lower than 50% included optimized fertilization and intercropping. Cover crops in orchard systems seemed to be the lowest mitigation practice with approximately 22%. However this small percentage can be accounted for by noting that in Aragon permanent crops are not widely practised. Whilst it could be a useful mitigation practice where applicable, in Aragon only 18% of the cropland is used for permanent crops such olive groves and vineyards (MAGRAMA 2013) and is as such, not as applicable in this region.

Table 5.5 shows the frequency distribution of the number of mitigation practices by Aragon farmers sampled. The survey offers evidence that 115 farmers out of 128 in the sample had adopted at least one mitigation practice which implies a very high overall adoption rate close to 90%. The sampled farmers adopted about 2.82 on average. Table 5.5 also demonstrates that only 13 (c.a 10%) of these sampled Aragon farmers had adopted none of these mitigation practices, and thus it does not explicitly consider an excess zeros problem. While the majority (83%) of the adopters had adopted 4 or fewer mitigation practices, only 17% of these farmers adopted 5 or more practices.

Table 5.5. Frequency distribution of mitigation practice adoption amongst sampled farmers

Mitigation practice counts	Frequency	Relative frequency
0	13	0.101
1	24	0.187
2	18	0.140
3	23	0.179
4	28	0.218
5	12	0.093
6	10	0.078
Total	128	1

1Out of 128 farmers sampled, 115 adopted one or more practices

Determinants of the intensity of mitigation practices adoption

The results of the Poisson and Negative Binomial models are shown in Table 5.6. The estimates associated with the marginal effects for the Poisson model are shown in Table 5.7. The likeness value of mean (2.82) and variance (3.09) of the dependant variable Mitigatpractices (adoption intensity of mitigation practices) suggested the appropriateness of using the Poisson model due to the equality property of the mean and variance. To adjust the standard errors in the presence of overdispersion (the variance is larger than the mean), the method of estimating the maximum pseudolikelihood (robust standard errors) has been applied, providing the robustness of the Poisson to distribution misspecification. The results from the Poisson and Negative Binomial models were very similar.

We performed the Wald statistical test to assess the significance of coefficients and the fit of the Poisson model with our dataset. The Wald test works by testing that all of the estimated coefficients are simultaneously equal to zero (Buse 1982). The null hypothesis that the coefficients are equal to zero would imply that no explanatory variable has an effect on the number of practices adopted. Based on the p-value associated with a chi-squared of 80.76 generated by the Wald test for the Poisson model, we can reject the null hypothesis at the given level of significance. This result indicates that the coefficients for our independent variables are not simultaneously zero and the inclusion of these variables helps to statistically improve the fit of the model.

Table 5.6. Coefficient estimates of the Poisson and Negative Binomial Regressions

	Poisson		Negative Binomial	
Variable	Coefficient	Standard error	Coefficient	Standard error
Constant	0.232	0.305	0.273	0.341
Age	-0.117	0.133	-0.200	0.140
Education	0.112	0.103	0.147	0.111
Landowner	-0.093	0.167	0.011	0.210
Size	0.015	0.051	0.005	0.052
Irrigation	0.049	0.087	0.011	0.107
Subsidies	0.330***	0.092	0.346***	0.111
Techadvice	0.398***	0.112	0.399***	0.115
Pacadvice	0.195**	0.088	0.200*	0.105
Awareness1	0.146	0.110	0.082	0.119
Awareness2	0.376***	0.109	0.371***	0.117
Number of observations	128		128	
ln L	-227.30		-274.41	
Pseudo R^2	0.100			
Wald Prob > chi2	0.000			
[1]Deviance Prob> chi^2	0.382		-	
[1]Pearson Prob> chi^2	0.847		-	

[1]Goodness-of-fit (Cameron and Trivedi 1986);Significant level of 10%(*), 5%(**) and 1%(***);

Deviance and the Pearson goodness-of-fit chi-squared tests help to assess the fit of the model (Cameron and Trivedi 1986). We cannot reject the null hypothesis that our data are Poisson distributed since the tests are not statistically significant. Therefore, we conclude from these results that our model fits reasonably well.

Table 5.7. Marginal effects for the Poisson Regression

Variable	Coefficient	Standard error
Age	-0.296	0.323
Education	0.294	0.269
Landowner	-0.254	0.476
Size	0.040	0.135
Irrigation	0.130	0.230
Subsidies	0.996***	0.292
Techadvice	1.038***	0.276
Pacadvice	0.541**	0.255
Awareness1	0.375	0.271
Awareness2	0.978***	0.268

Significant level of 10%(*), 5%(**) and 1%(***)

Our results suggest that the factors that are positively influencing the farmer's decision to adopt or implement a greater number of agricultural practices are: advice on practices technology and management, advice on the CAP, economic incentives for the adoption of these practices and motivation or awareness of environmental type. We tested the correlations between the explanatory variables by practice and these factors were not significantly correlated in the model. However, the advice about the CAP and the economic incentives variables can be related since increases in the farmer’s knowledge about the CAP from adequate sources might hence increase the incentives that the farmers are receiving thus far.

According to our study, keeping the other variables constant, if you increase the advice about the management of the practices, it is expected that mitigation practices adoption would increase significantly. In the same way, an increase in CAP advice would mean an increase in the mitigation practices adoption. These results concur with the studied literature (Cary et al. 2001; Prager and Posthumus 2010; Tambo and Abdoulaye 2012) which states that farmers who attended training courses and had access to technical and policy information adopted more mitigation practices. Further if environmental awareness (awareness2) was increased, it is expected that the mitigation practices adoption would also increase. The fact that increasing the awareness of climate change would lead to increased adoption of mitigation measures is concurrent with many previous studies (Morris and Potter 1995; Prokopy et al. 2008; Tambo and Abdoulaye 2012; García de Jalón et al. 2013).

This study showed that economic factors have a very significant impact on the adoption of mitigation practices by farmers surveyed in Aragón. For example, for an increase of *subsidies*, it is expected that the mitigation practices adoption would increase. Smith et al. (2008) showed that the economic limitations may be a strong barrier to the adoption of mitigation practices, reducing the agricultural GHG mitigation to less than 35% of the total biophysical potential by 2030. A broad range of research focuses on financial incentives measured as monetary compensation or subsidies by mitigating GHG emissions efforts, but behavioural barriers including educational, social and policy constraints have been found to limit the effect of economic incentives on adoption of mitigation practices (Prager and Posthumus 2010; OECD 2012b).

The other variables involved in the equation, although not significant, showed a sign of regression coefficient in line with our assumptions, which may be due to the small number of collected observations.

Determinants of individual mitigation practice adoption

The logit binomial model provides a more detailed understanding of the factors influencing the adoption of agricultural mitigation practices. These results define the influence of the factors for each individually considered mitigation practice (Table 5.8; Table 5.9).

Subsidies and Awareness2 (environmental motivation) seem to be key factors in the adoption of cover crops as hypothesized. However, the Landowner variable negatively affected the adoption of cover crops implying that our hypothesis was incorrect and that the fact of being a landowner in effect reduces the likelihood to adopt the practice of cover crops. However the limited extent of permanent crops in the sampled area may have affected this result.

Table 5.8. Coefficient estimates and marginal effects of the Binomial Regressions (I)

	Cover crops in orchard systems		Reduced tillage/no-tillage		Fertilization with animal manures	
Independent variable	Coefficient	Marginal effects	Coefficient	Marginal effects	Coefficient	Marginal effects
Constant	-1.201(1.593)		-1.384(1.455)		-2.975(1.250)	
Age	-1.031(0.814)	-0.109(0.065)	-1.522(0.580)***	-0.357(0.131)	0.916(0.570)	0.218(0.124)
Education	0.752(0.569)	0.097(0.074)	0.654(0.479)	0.141(0.105)	-0.413(0.441)	-0.102(0.109)
Landowner	-1.684(0.824)**	-0.332(0.187)	-0.244(0.690)	-0.050(0.135)	0.560(0.770)	0.137(0.182)
Size	-0.271(0.277)	-0.036(0.036)	0.422(0.224)*	0.090(0.047)	0.127(0.205)	0.0319(0.051)
Irrigation	-0.144(0.419)	-0.019(0.056)	-0.068(0.431)	-0.014(0.092)	0.512(0.371)	0.128(0.092)
Subsidies	1.536(0.526)***	0.272(0.108)	1.127(0.825)	0.205(0.117)	-0.206(0.500)	-0.051(0.124)
Techadvice	0.830(0.603)	0.110(0.071)	1.273(0.475)***	0.271(0.098)	1.284(0.439)***	0.310(0.099)
Pacadvice	-0.084(0.580)	-0.011(0.075)	0.932(0.524)*	0.177(0.089)	0.819(0.503)	0.198(0.115)
Awareness1	0.773(0.632)	0.095(0.068)	-0.195(0.550)	-0.041(0.113)	0.053(0.467)	0.013(0.116)
Awareness2	1.233(0.626)**	0.161(0.075)	0.306(0.503)	0.065(0.107)	0.595(0.471)	0.147(0.115)
Likelihood ratio	-55.26		-66.20		-75.62	
Observations	128	128	128	128	128	128

Standard errors are in parenthesis; Significant level of 10%(*), 5%(**) and 1%(***)

Table 5.9. Coefficient estimates and marginal effects of the Binomial Regressions (II)

	Optimized fertilization		Crop rotations		Intercropping	
Independent variable	Coefficient	Marginal effects	Coefficient	Marginal effects	Coefficient	Marginal effects
Constant	-0.964(1.282)		-0.710(1.411)		-4.969(2.00)	
Age	-0.165(0.538)	-0.040(0.131)	-1.555(0.608)**	-0.343(0.139)	0.331(0.631)	0.066(0.131)
Education	0.535(0.423)	0.131(0.102)	0.901(0.508)*	0.171(0.095)	-0.452(0.550)	-0.087(0.104)
Landowner	0.162(0.758)	0.040(0.184)	0.876(0.714)	0.188(0.166)	-1.441(0.961)	-0.330(0.231)
Size	-0.289(0.231)	-0.071(0.057)	-0.140(0.247)	-0.025(0.045)	0.325(0.279)	0.062(0.050)
Irrigation	-0.253(0.377)	-0.062(0.093)	-0.313(0.479)	-0.057(0.086)	1.118(0.359)***	0.213(0.070)
Subsidies	0.641(0.514)	0.159(0.125)	1.353(0.707)*	0.197(0.079)	2.749(0.608)***	0.591(0.104)
Techadvice	1.097(0.427)***	0.264(0.097)	0.811(0.513)	0.151(0.096)	0.061(0.493)	0.011(0.093)
Pacadvice	0.976(0.521)*	0.238(0.121)	1.597(0.513)***	0.230(0.064)	-0.164(0.490)	-0.030(0.090)
Awareness1	0.500(0.528)	0.122(0.125)	0.155(0.520)	0.029(0.098)	0.888(0.664)	0.155(0.099)
Awareness2	0.769(0.508)	0.187(0.119)	1.122(0.465)**	0.210(0.088)	2.098(0.732)***	0.372(0.103)
Likelihood ratio	-75.35		-62.42		-59.06	
Observations	128	128	128	128	128	128

Standard errors are in parenthesis; Significant level of 10%(*), 5%(**) and 1%(***)

The practice of reduced tillage and direct seeding seems to be more influenced by Age, Size, Techadvice and Pacadvice. This implies that older farmers are less likely to adopt the practices of reduced tillage and direct seeding, suggesting these relatively new practices are not seen as viable by more traditional farmers. This agrees with Cary et al. (2001) who found that younger farms are often more aware of soil degradation and so reducing tillage and directly sowing their seeds could be seen as advantageous to a young well informed farmer. Prager and Posthumus (2010) similarly noted a greater uptake amongst young farmers and larger farm holdings, concurrent with our results. As hypothesized, increased dissemination of information about the management of reduced tillage and more advice concerning relevant agricultural policy would incentivize the adoption of this practice.

The influence of Techadvice and Pacadvice seem to be common factors in the adoption of many mitigation practices, especially concerning optimized fertilization. This influence could be due to the close link between optimized fertilization, scientific advances, technological transfer and agricultural and environmental policy objectives. Furthermore, the influence of Techadvice seems to have a positive impact on the adoption of animal manure. These results reflect that which has been discussed previously regarding the technical knowledge required for the storage, handling and application of animal manure.

Crop rotation is positively influenced by Education, Subsidies, Pacadvice and Awareness2. This coincides with the relevant literature which has previously found that farmers with a technical education are expected to be more likely to adopt a mitigation practice (Rahelizatovo and Gillespie 2004; Knowler and Bradshaw 2007; Ward et al. 2008; Tambo and Abdoulaye 2012; Archie 2013). Similarly to reduced tillage, as the farmer ages, the crop rotation rate is expected to decrease by 0.343, perhaps for the extra labour and change in working practice implied, normally assumed to be a bastion of the young.

Factors influencing the adoption of intercropping are Subsidies, Irrigation and Awareness2. As intercropping implies a greater cultivated area and hence greater water demand, thus those farmers who already have an established network for irrigation would be more likely to implement intercropping. Similarly to the uptake of cover crops, increased awareness of environmental welfare would also imply a greater likelihood that the practice would be adopted.

Several studies found that the farmers were not motivated to adopt mitigation or agri-environmental practices if they did not receive compensation for implementing them (Poe et al. 2001; Bracht et al. 2008; Hellerstein et al. 2002). The financial incentive seems to be the most attractive option for the farmer’s adoption decision (Prager and Posthumus 2010). Subsidies are significant to farmers and this variable is significant in practices that may receive direct or indirect financial incentives in the form of subsidies. Crop rotation is the only practice that currently receives direct subsidies in Aragon out of our six selected mitigation practices, however intercropping and cover crops may be eligible for subsidies when associated with legume species subject to the environmental commitment of the CAP. The practices that do not receive subsidies may require a higher level of private investment and therefore their implementation relies only on the possible economic benefit for the farmer. As most farmers already use fertilizer, a change to optimized fertilizer or animal manure does not necessary imply a great modification to the status quo and reduced tillage if anything requires less work and thus financial incentives for these practices are not so imperative.

5.5 Conclusions

There are some major limitations of our findings. First, the study does not address the full range of mitigation practices. The list of selected mitigation practices is limited and only included the measures that are likely to be relevant in the region. This selection is based on the applicability of the practice given the current structure of the farming systems, agro-climatic limitations and the production factors of the case study. The selected measures addresses crop and soil mitigation, since over ninety percent of the farming systems are cropland. Livestock mitigation measures are not considered. Second, the expert panel for the MCA was only composed of academics and despite many of them belonging to policy committees and policy advisory boards; it could be more policy relevant to include the views of policy-makers, practitioners and farmers. The MCA included qualitative criteria, resulting in difficult comparison among experts' opinions. A derived shortcoming is that the qualitative criteria is limited in capturing variability among the respondents and beyond that, some of the qualitative criteria seem to be reasonable interlinked and overlapping; therefore the low variability of our results in the different climate scenarios may be a consequence of using qualitative criteria. In spite of this shortcoming, farmers are more likely to respond to qualitative than quantitative criteria when they perceive that the question is not directly related to their expertise. In addition some of the open questions provide limited information for the quantitative process. The key question of cost-effectiveness was not explicitly considered. As an alternative, the responses were used to estimate the effort to benefit ratio of each measure. Third, the survey sample is relatively small and it is not necessarily representative of the entire Aragon region, although, the gender, education and land holding structure are fairly in line with the region's demographics. It would be of great interest to conduct a similar study with a larger number of participants to consolidate our preliminary findings. Finally, the econometric models applied to the survey results only provide an evaluation of the effect – positive or negative – of the determinants on the adoption of practices and do not provide a monetary evaluation. The influence of different determinants on adoption of mitigation practices is a useful factor to define the measures that are likely to be adopted and evaluate barriers to implementation. Future research is needed in order to further understand the underlying reasons for adoption of mitigation practices and how local knowledge can be used in the wider policy context.

Despite these limitations, the analysis advances our knowledge of differing public support for climate change mitigation policy by providing increased comprehension of the variety of reasons farmers oppose or support mitigation policies and their relationship to the socio-demographic characteristics which could be used to predict mitigation policy support in a geographically and socially diverse area. The methodology developed could be applied on a larger scale, in different regions and under different climatic scenarios.

The study suggests that the design of agricultural mitigation strategies in Aragon must give additional importance to the adoption of agricultural practices such as cover crops in orchard systems and optimized fertilization. These were selected by the expert panel to be the most suitable practices under both the current climate and a supposed warmer, drier one given their capacity to improve water quality and enhance soil carbon sequestration. Both practices were widely accepted by experts and had a relatively low effort to benefit ratio in terms of implementation costs and mitigation potential. The results from the literature review suggest that the adoption of these practices could benefit the agricultural mitigation in Aragon by soil carbon sequestration rates ranging between 0.65 -1.55 t CO_2 ha^{-1} per year for at least 7.5% of the total croplands and 0.36 – 0.62 t CO_2 ha^{-1} per year for all the croplands area. Furthermore, the adoption of optimized fertilization has been reported to contribute to the dissemination and transfer of knowledge of scientific research and innovation to the farmers by establishing a channel of communication where farmers can be made aware of such advances. No single strategy is completely effective and a combination of regional plans, advisory services, research and private measures, should be implemented.

Our results confirm the main findings of previous studies which have proposed that both financial and non-financial incentives affect the farmer’s decision to adopt mitigation practices. The main factors influencing the adoption rate of the mitigation practices considered in this study were; whether or not financial subsidies were received, whether technical advice was readily available, whether political advice was accessible and the environmental concern of individual farmers. Thus the adoption of these practices should be encouraged with policy measures which include financial incentives while promoting environmental awareness and technical training. As these practices are widely seen to be advantageous, in terms of their mitigation potential and soil quality, it stands to reason that the better informed the farmers are, the more likely they are to adopt these beneficial practices. The dissemination of scientific advances, technical information and agricultural policies relating to these mitigation practices reach the farmers by extension services, however great improvements are needed given that current farm advisory services are limited and poorly funded (EC 2009b), especially in Spain. Finally, it is not surprising that financial incentives play an important role in encouraging the agricultural population to adopt cover crops, intercropping and crop rotation. Advisory services need interventions in order to ensure adequate access to policy and technical information, especially for the adoption of crop rotations, optimized fertilization, reduced or zero tillage and fertilization with animal manures.

The results show that there is considerable potential for improving agricultural mitigation and support for mitigation policies in the region. Motivation and barriers are affected by demographic determinants, which indirectly influence individuals' support for mitigation policies (Iglesias et al. 2012b). In this study, the main socio-demographic determinant which affected farmers' likelihood of adoption is knowledge. Future work may consider a deeper assessment of farmers' attitude towards climate change as well as the role of socio-demographic determinants. Consequently, this would be particularly relevant for increasing farmers' education level in order to enhance support for mitigation policy. To this end, a choice modelling method based on farmers' opinion using field surveys seems to be particularly appropriate.

6. Mitigation: Marginal Abatement Cost Curves

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Objective: To develop farming and policy tools to help to reach mitigation targets and enable farmers, advisors and policy makers to select the most appropriate and cost-effective practices for Mediterranean farming systems, soils and climates.

Contribution: B. Sánchez designed the study, coordinated the research team and was the lead author of the paper. She carried out the quantitative analysis.

6.1 Abstract

A portfolio of agricultural practices now exist that contribute to reaching European mitigation targets. Among them, the management of agricultural soils has a large potential for reducing atmospheric CO_2 emissions. Many of the practices are based on well tested agronomic and technical know-how, with proven benefits for farmers and the environment. A suite of practices has to be used since none of the practices could provide a unique solution by itself. However, there are limitations in the process of policy development: (a) agricultural activities are based on biological processes and thus, these practices are location specific and climate, soils and crops determine their agronomic potential; (b) since agriculture sustains rural communities, the costs and potential implementation have to be also regionally evaluated and (c) the aggregated regional potential of the combination of practices has to be defined in order to inform abatement targets. We believe that, when implementing mitigation practices, three questions are important: Are they cost-effective for farmers? Do they reduce GHG emissions? What policies favour their implementation? This study addressed these questions in three sequential steps. First, mapping representative farming systems and soil management practices in the European regions to provide a spatial context to upscale the local results. Second, using a Marginal Abatement Cost Curve (MACC) in a Mediterranean case study (NE Spain) for ranking soil management practices. Finally, using a wedge approach of the practices as a complementary tool to link science to mitigation policy. A set of soil management practices were found to be financially attractive for Mediterranean farmers. Significant abatements could be achieved at cost below the reference threshold of carbon cost of 100€/tCO_2e (e.g., 1.34 MtCO_2e in the case study region). The quantitative analysis was completed by a discussion of potential farming and policy choices to shaping realistic mitigation policy at European regional level.

Keywords: Cost-effectiveness; Marginal abatement costs curves; Mitigation strategies; Stabilisation wedges; Soil organic carbon management.

6.2 Introduction

The European Union (EU) targets for reducing CO_2 emission have a clear agricultural contribution, due not only to technical feasibility, but also to potential implementation since the agricultural sector is subject to intervention (EC 2013b). Therefore, the practices that could be supported by agricultural policy represent a suitable subject for research. However, given the complex interactions of agricultural production with the environment and the sustainability of rural communities, these practices need to be evaluated from agronomic and socioeconomic perspectives.

The collective EU target for all the Member States is to reduce GHG emissions by 20% in 2020 compared to the 1990 baseline and there are some individual country targets such as Spain's commitment to reduce GHG national emissions by 10% in 2020 compared to the 2005 baseline (EC 2013a). In the global effort to reduce GHG emissions, the mitigation potential of agriculture can significantly help to meet these emission reduction targets (IPCC 2014b). The CO_2 emissions reductions to achieve the EU target depend on the quantitative details of mitigation potential of the practices and the agricultural policy that influences farmers' decisions (Smith et al. 2007a). Agricultural emissions from livestock and soil and nutrient management contribute to approximately half of the anthropogenic GHG emission (5.0-5.8 GtCO_2eq/yr) of the AFOLU sector (Agriculture, Forestry, and Other Land Use), which in turn represents a quarter of the global GHG emissions (49 ± 4.5 GtCO_2eq/yr) in 2010 (IPCC 2014b).

The role of agricultural management to provide soil organic carbon (SOC) sequestration was recognised by the Kyoto Protocol in the United Nations Framework Convention on Climate Change (UNFCCC 2008). Smith (2012) and the IPCC (2014b) indicated that SOC sequestration has a large, cost- competitive mitigation potential to meet short to medium term targets for reducing the atmospheric CO_2 concentration. The optimistic global estimates are challenged in some local conditions (Lam et al. 2013; Powlson et al. 2014; Derpsch et al. 2014). However, it is clear that smart soil management leads to improve soil health, reduce degradation and depletion of soil carbon, and reduce emissions (Lal 2013). Therefore soil management changes will benefit soil carbon stocks and, in turn, optimise crop productivity (Ingram et al. 2014; Lal 2004, Freibahuer 2004; Smith 2012).

A set of practices with proven benefits to the environment and farmers has been recognised (Lal 2013; Freibahuer 2004; Smith et al. 2008; Smith 2012). These practices include, among others: a more efficient use of resources and integrated nutrient managements with organic amendments and compost; reduced and no tillage; crop rotations; legumes/improved species mix; growing cover crops during the off seasons; residue management; and land-use change (conversion to grass/trees). However, knowledge on the implementation and cost of specific mitigation practices and technologies at the farm level is limited and fragmented (MacLeod et al. 2010, Smith et al. 2007a; Bockel et al. 2012; ICF 2013). This knowledge is necessary to facilitate government's understanding of potential policy development.

Here, we focus exclusively on practices that contribute to the abatement targets of the EU and also have clear benefit on the SOC content. This choice is guided by four factors: (a) SOC enhancement practices have a proven essential role for global mitigation potential; (b) the SOC enhancement practice is an indicator of long term land productivity and sustainability; (c) improved SOC content requires less nitrogen application, and in turn less N_2O emissions, a major greenhouse gas; (d) improved SOC contributes indirectly to soil water improvement by improving the physical soil properties that lead to water retention, therefore this is also an essential adaptation measure to climate change in semi-arid regions linking mitigation and adaptation practices.

The methods used to evaluate the farming choices that contribute to reach a mitigation potential range from purely socio-cultural approaches (Morgan et al. 2015) to technical evaluations in field studies (Derpsch et al. 2014). A method that has been proven valuable to communicate science results for mitigation policy is the Marginal Abatement Cost Curve (MACC). The MACCs have been derived for the major sectors (McKinsey & Company 2009), for waste reduction strategies (Beaumont and Tinch 2004; Rehl and Müller 2013) and for agricultural greenhouse practices in some countries such as United Kingdom (MacLeod et al. 2010; Moran et al. 2011a), Ireland (O'Brien et al. 2014), France (Pellerin et al. 2013) and China (Wang et al. 2014) to inform policy development. Further to the MACC approach, Pacala and Socolow (2004) created the concept of stabilisation wedges to clarify how mitigation options could help stabilize atmospheric CO_2. This concept has been used widely as it provides a clear-cut way to link science to policy. The stabilisation wedges have been derived for the major carbon-emitting activities by means of decarbonisation of the supply of electricity and fuel, and also from biological carbon sequestration by forest and agricultural management (Pacala and Socolow 2004; Grosso and Cavigelli 2012).

We believe that, when implementing mitigation practices, three questions are important: Are they cost-effective for farmers? Do they reduce GHG emissions? What policies favour their implementation? This study addressed these questions in three sequential steps. First, mapping representative farming systems and soil management practices in the European Union to provide a spatial context to upscale the local results. Second, evaluating a Marginal Abatement Cost Curve (MACC) for ranking mitigation soil and crop practices in a Mediterranean region. Finally, using a wedge approach of the practices as a complementary tool to link science to mitigation policy.

In order to provide realism to the analysis we selected a representative case study in NE Spain that exemplifies semiarid Mediterranean agricultural systems. This intensive agricultural region produces rainfed and irrigated crops (c.a. 89% and 11% respectively); the conventional management undertaken during decades - intensive soil tillage and low crop residue input - have led to the soil degradation. Thus we restrict our attention to the strategies that are relevant to semiarid environments and may have linkages to adaptation. Here we consider only practices that produce additive effects, in order to calculate the aggregated abatement potential for the entire region as a result of the implementation of all the selected practices simultaneously.

6.3 Methods and data

6.3.1 Overall approach

Our approach to estimate cost-effective management of agricultural soils for greenhouse gas mitigation is summarised in Figure 6.1. The methodology included three sequential steps. First, we defined a relatively limited number of European farming systems and the use of crop and soil management with abatement potential. In this study we evaluated only the practices that imply small management changes and that could be easily implemented by farmers without large investments or infrastructure. Second, we estimated the cost-effectiveness and the abatement potential of the selected practices by MACC in a Mediterranean case study (NE Spain). We compared our results with other European regions which are leading emitters of GHG from agriculture (e.g., France and United Kingdom; De Cara and Jayet 2011). Third, we built SOC abatement wedges to prioritize practices by abatement potential rather than monetary benefits. Finally, we linked all the results to facilitate farming and policy choices.

This methodology was implemented in Aragón, NE Spain, since it is the fourth largest agricultural region in the country and can illustrate Mediterranean agricultural systems. We considered the abatement potential by the effect of each practice on the SOC content, since the experimental data available included it for all practices.

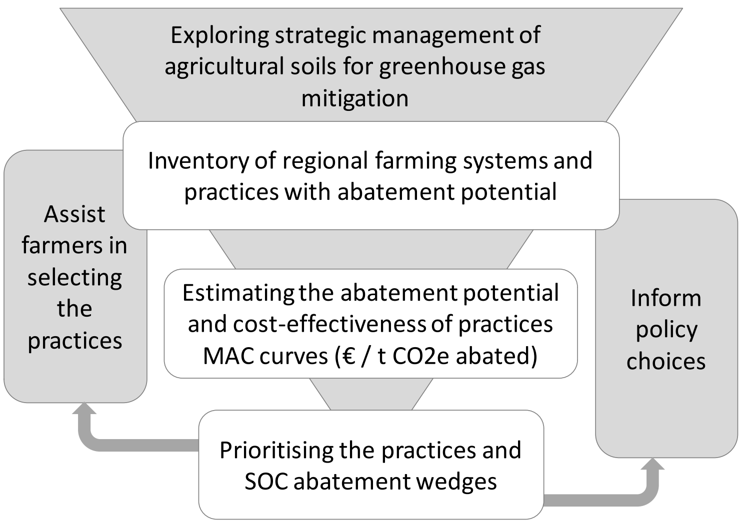


Figure 6.1. Structure of the study to estimate the cost-effective crop and soil farming practices for GHG mitigation

6.3.2 Inventory of European farming systems and SOC management

Here we aimed to illustrate representative farming systems and adoption of soil management practices improving SOC flows and stocks in Europe. We developed a database for all EU-27 member states at regional (NUTS2) level. The statistical data on historical and current agricultural land use was from official databases (e.g., EUROSTAT) and from MITERRA-Europe model. A further description of MITERRA-Europe can be found in Velthof et al. (2009) and Lesschen et al. (2011). The indicators in the database included main farming system (largest occupied area), total farming area (UUA) and the use of SOC management practices (%) based on areas relative to arable land (Table 6.1). We aggregated 21 farm types derived from the European Commission research project SEAMLESS (http://www.seamless-ip.org) into six main farming systems: Field crops, Permanent crops, Pasture and grasslands, Industrial crops, Horticulture and Mixed farms (See Table A4.1 in Annex 4). Part of the management data was derived from the Survey on Agricultural Production Methods (SAPM); see also Council regulation (EC) No 1166/2008, which was held together with the FSS in 2010.

Table 6.1. Indicators summary for the inventory of European farming systems and SOC management

Indicators	Description / Comment	Source of information and gaps
Main farming systems	Aggregation into six main farming systems: Field crops, Permanent crops, Pasture and grasslands, Industrial crops, Horticulture and Mixed farms.	Data derived from the SEAMLESS project and EUROSTAT regional and national statistics 2008. A detailed description can be found in Andersen (2010). Missing data for Romania, Bulgaria, Cyprus and Malta missing.
Total utilized agricultural area (UAA)	Area expressed in hectares and based on the sum of all crop areas, including rough grazing.	Data derived from EUROSTAT regional and national statistics 2008.
Use of SOC management practices based on areas relative to arable land	Percentage of land under a certain management practice compared to the total area of arable land (UAA). Agricultural management practices which are relevant for soil carbon. Organic farming excluding the farms still in conversion.	Data derived on SAPM survey from 2010 and derived on the 2010 FSS statistics at regional level from EUROSTAT (e.g., organic farming).Some missing data of SOC management practices for Germany regions.

6.3.3 Generating the marginal abatement cost curves

The cost-effectiveness assesses the abatement potential of these practices subject to economic constraints by determining the specific marginal cost of reducing CO_2 emissions by one tonne. Following the approach of previous studies to cost-effectiveness analysis on agricultural emissions abatement (e.g. Moran et al. 2011b), we assumed that maximising gross margin is a key objective to the farm decision making. The GHG emissions abatement is considered a benefit for the society and is the primary goal for mitigation policies, however farmers are often more interested in short term financial gains from higher yields or lower input requirements (Ingram et al. 2014; Sánchez et al. 2014a). Here, we focused on the benefits to farmers, including greater efficiency of input use and profitability. Thus, we estimated the cost-effectiveness as the change in gross margin per tonne of CO_2e abated, being the gross margin the surplus of output (price x quantity) over variable costs and assuming that fixed costs are less important for short-term decision making by definition. The cost-effectiveness estimates the marginal cost of each agricultural practice to mitigate CO_2 in € per tonne of CO_2e abated:

$$CE_{p,c} = \frac{\Delta GM_{p,c}}{\Delta SOC_p} \quad (1)$$

Where $CE_{p,c}$ is the cost-effectiveness for each practice p and crop c, the $\Delta GM_{p,c}$ is the change in gross margin related to practice p and crop c and ΔSOC_p is the change in SOC associated with practice p. The calculations of cost-effectiveness were undertaken at the per hectare level. The effect on SOC was extended to the regional scale by multiplying by the production level (area planted) of each crop. The change in gross margin $\Delta GM_{p,c}$ was calculated as the change in the output for each cropping activity when the mitigation practice is implemented.

Figure 6.2 outlines the MACC approach to rank the mitigation practices in terms of their cost-effectiveness in € per tonne of CO_2e abated and at the same time to show the total abatement potential in tonnes by practice for the case study region. Each of the bars represents an individual mitigation practice. The vertical axis represents the cost-effectiveness, where negative cost values mean savings. The horizontal axis represents total abatement potential, the wider these bars the greater its abatement potential.

The MACC plots the abatement potential that could be achieved by i) less than zero cost practices which will probably result in direct financial benefit (cost-beneficial or win-win practices); ii) positive costs practices that are still below the social cost of carbon or some policy equivalent measure as the shadow price of carbon (SPC) that reflects mitigation targets (cost-effective practices) or; iii) positive costs practices that are above the social cost of carbon and reach small additional abatement at increasingly high marginal cost (expensive practices).

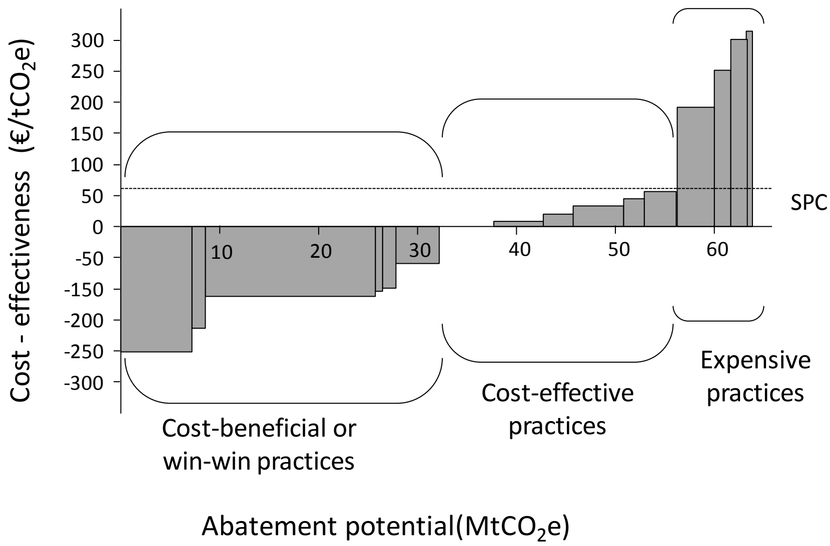


Figure 6.2. Theoretical example of a Marginal Abatement Cost Curve (MACC)

6.3.4 Regional crop types, practices with abatement potential and costs

This methodology was implemented in Aragón, a semiarid region located in NE Spain; it is a large region of 47,700km^2. About one fourth of the territory is agricultural land. The climate in the agricultural area is Mediterranean with continental influence; with mean annual temperatures ranging from 7 ºC to 15 ºC and mean annual precipitation from 300 to 800 mm.

At present, agricultural activities in Aragón are responsible for about 3.8 million tCO_2eq, over 20 % of total GHG emissions in the region and from which 1.85 million tCO_2eq are released just by crop cultivation (MAGRAMA 2012). In most cases, the current agricultural management is based on intensive tillage, high mineral and organic fertilization and the use of monocultures (Álvaro-Fuentes et al. 2011), although more sustainable practices are evolving in recent years. Consequently, small changes in the current management could have large potential for improving regional and national mitigation commitments (Sánchez et al. 2014a).

First, we selected the target crops representative of the case study region, second the most relevant mitigation practices and finally we estimated the cost-effectiveness in € per tonne of CO_2e abated and the total abatement potential of the mitigation practices and used a MACC to rank them.

The sources of data included: (a) national statistical databases; (b) local and European published databases (EUROSTAT; Sánchez et al. 2014a; Smith et al. 2008); (c) existing experimental evidence and literature; and (d) data derived from an expert group. Readers are asked to note that the sources and the data used are available in Annex 4. The expert group was conducted as a workshop in February 2014 with 10 participants from the policy and farm advisory communities, to validate the databases, to assess the applicability and relevance of theoretical abatement practices and to validate costs data; this is reported in detail in the European Commission research project SmartSOIL (www.smartsoil.eu). The inclusion of a group of experts to validate statistical data and provide additional qualitative information on barriers and incentives has been used in similar studies (Moran et al., 2011; MacLeod et al., 2010).

Target crops

The most significant crop systems were identified and their gross margin was estimated as the surplus of output over variable costs (see Table A5.2). The database used was published by the Spanish Agricultural Census. The most significant crops are wheat (rainfed and irrigated), barley (rainfed and irrigated), maize (irrigated), alfalfa (irrigated), almonds (rainfed), vineyards (rainfed) and olives (rainfed). These selected crops account for 75% of the total cropland area of the region.

Practices with abatement potential

The selection of practices (Table 6.2) was based on previous studies and the abatement potential measured as CO_2 equivalent including direct CO_2 and N_2O reductions (Sánchez et al. 2014a; Smith et al., 2008). The six practices identified are already implemented by some farmers in the case study region, and could be scaled up further to contribute to mitigation policy in other European regions; the practices are defined below.

Table 6.2. Summary of the selected mitigation practices and the abatement rate estimations for the Aragón region

No	Mitigation practices	Description	Estimated abatement rate (tCO2e ha-1yr-1)		
			Mean	Low	High
P1	Cover crops in field crops Cover crops in tree crops	Cover crops in cereals and orchards are planted crops in order to improve soil fertility and water use (Marquez-Garcia et al. 2013). The cover crop practice may increase soil carbon, reduce soil erosion and also has a high potential to reduce GHG emissions, especially N2O, in the Mediterranean areas (Sanz-Cobena et al. 2014).	0.42 1.10	-0.21 0.65	1.05 1.55
P2	Minimum tillage	Minimum tillage implies avoiding as far as possible tillage practices. Soil carbon storage is increased through reducing microbial decomposition and, particularly in rainfed systems, throughout the increase in C input (Álvaro-Fuentes et al. 2014).	0.47	0.23	0.71
P3	Residue management	Residue management is defined here as the practice that retains crop residue on soil surface, eliminating stubble burning or stubble removal for livestock use. It may be highly effective to reduce GHG emissions (Smith et al. 2008).	0.17	-0.52	0.86
P4	Manure fertilization	Manure fertilization is the use of animal manures for crop fertilization and to enhance carbon return to the soil. An increase in N_2O emissions can be associated with the manure management undertaken (Freibauer et al. 2004).	0.22	0.10	0.33
P5	Optimized fertilization	Optimized fertilization is defined here as the increase in nitrogen use efficiency throughout the adjustment of application rates to crop needs, fertilizer placement or split applications. Precise application of fertilizers can help to reduce nitrate leaching losses and N_2O emissions (Smith et al. 2008).	0.49	0.36	0.62
P6	Crop rotations (with legumes)	Crop rotation with legumes is recognized for its capacity to increase soil carbon content and to reducing the requirement for nitrogen fertilizer, thereby reducing N2O emissions from fertilizer use (Lal 2004).	0.84	0.08	1.60

Note: The estimated abatement rate (CO_2 mitigation) were derived from Sánchez et al. (2014a) for most of the practices except cover crops for cereals and residue management which were derived from Smith et al. (2008), and validated by the Expert Group (Feb 2014). Positive values represent SOC increases

Costs

Table 6.3 and Table A4.3 (Annex 4) provide the assumptions and estimations of private costs and benefits (i.e. to the farmer) and yield effect for implementing each practice per crop in the region. The private costs of implementation included i) investment costs derived from new needs on seeds, machinery or equipment; ii) cost of farm operations associated with the practice such as additional spraying or nutrients inputs; and iii) displacement cost of the practice such as loss of production or saleable product (e.g. loss of cereal straw value for incorporation into soil). The private benefits were the cost savings from reductions of inputs or operation needs.

Table 6.3. Private cost assumptions and yield effect of implementing the mitigation measures by crop type in Aragón

Measure	Target crops	Private costs (€/ha)	Private benefits (€/ha)	Yield effect (%)
1. Cover crops	Maize ir. Almond ra. Vineyard ra. Olives ra.	Seeds + annualized cost for a pneumatic seed-drill for woody crops	N purchase costs reduced by 23% in cereals	Yield increase for maize (1.06 to 1.11%) and unaffected for orchards
2. Minimum tillage	Barley ra. Barley ir.	Annualized cost for a direct seed drill	Avoided costs of mouldboard plough	Yield increase (~1.55%)
3. Residue management	Wheat ra. Wheat ir. Barley ra. Barley ir.	Loss of straw value for incorporation into soil	No benefit accounted	Yield unaffected
4. Manure fertilization	Barley ra. Barley ir. Maize ir.	Operational cost of manure transport (max 3km) and applying	Mineral fertilizer cost avoided for barley and N purchase costs reduced by 60% for maize	Yield unaffected
5. Optimized fertilization	Wheat ra. Wheat ir. Barley ra.	Annual soil analysis	N purchase costs reduced by 23% for wheat and doses lower than 60kgN/ha for barley	Yield increase (1.03 to 1.05%)
6. Crop rotations (legumes)	Wheat ra. Barley ra.	Not cost accounted	N purchase costs reduced by 50%	Yield increase (1.35 to 1.40%)

Notes: ra. means rainfed; ir. means irrigated

Barriers and incentives

An expert group provided further information about the barriers and incentives for implementing the practices. The barriers included climatic constraints (such as limiting precipitation threshold for applying rotations with legumes in arid areas), agronomic constraints (such as the possible water and nutrients competition between crops in rainfed systems with cover crops), and social constraints (such as acceptance). Incentives included demonstration of the benefits of practices at farm level and direct policy support. Although barriers and incentives were not considered quantitatively in our analysis, we used the information to include a qualitative narrative that contributed to the interpretation and discussion of the results.

6.3.5 Generating SOC abatement wedges

Here we applied the stabilisation wedges concept (Pacala and Socolow 2010) to illustrate the regional abatement potential of the selected practices in order to inform agricultural and climate policy. In Figure 6.3, the area of the polygon A represents the projections of GHG emissions in a business as usual scenario. The area of the triangle B represents the stabilization wedge of the SOC strategies; this area is further composed of the contribution from each individual practice.

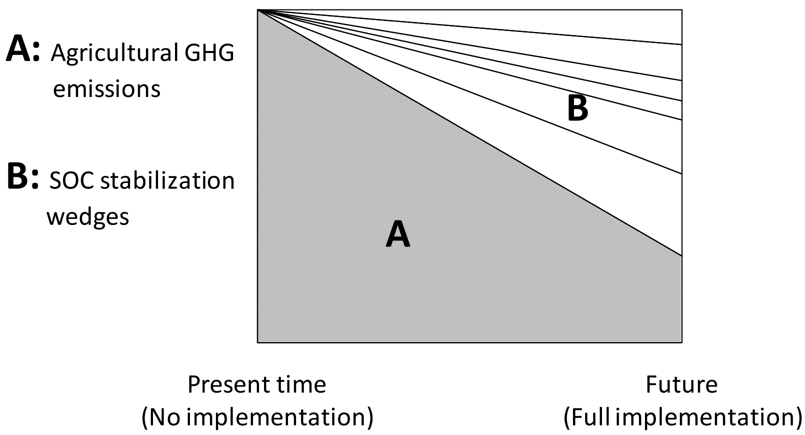


Figure 6.3. Simplified representation of the stabilization wedges of the SOC strategies based on the concept of Pacala and Socolow (2010).

6.3.6 Limitations and assumptions

There are important limitations of our analysis. First, we addressed only crop and grassland farming systems and crop and soil mitigation practices. Although livestock systems were not considered explicitly in the study, it was included in the farming classification of the inventory (i.e., mixed systems). Second, the static nature of our MACC, as it just considered a single year for the calculation that was also outlined by Ward (2014). Thus, our MACC was unable to account for the effects of temporal changes in the SOC sequestration rate of the mitigation measures (Álvaro-Fuentes et al. 2014) or improvements in soil structure and workability that might reduce costs and change the cost-effectiveness of the measures. Furthermore, we did not consider issues such as potential SOC saturation or the effects of occasional tillage. Third, our analysis did not consider ancillary costs and benefits of the GHG emissions reduction and omits the interaction of measures (MacLeod et al. 2010), since it required a detailed assessment of interaction factors which we have not been able to find in the literature. Neither was considered the interaction with behavioural aspects which can have a substantial influence on farmer decision making. As an alternative, we involved the expert judgment in our study to outline the uptake barriers and incentives of practices according to technical, social and economic drivers. Finally, the lack of existing key data and empirical evidence with respect to the effect of implementing practices in terms of SOC, GHG emissions, yield impact and costs at the regional level. Where possible we used data specific to the region, but some of the elements for the calculations had to be based on assumptions from studies conducted in other semiarid areas and on expert judgment (see Table 6.3 and Annex 4). We had to calculate the effect on three variables (private costs, private benefits and yield effect) of the six abatement practices selected, that is a total of 18 estimations. In most cases (over 80 percent of the variables), the regional data used was collected from published peer reviewed experimental evidence in the region, data published in the statistical yearbooks of the Ministry of Agriculture, and reports of pilot demonstration projects financed by the European Commission (references provided in Annex 4). A few exceptions of additional data were necessarily made to complete the database. First, expert judgement was used in four cases to estimate the private costs and benefits, in particular for the effect of crop rotations with legumes, and the yield effect of residue management and manure fertilisation. Second, the yield effect of minimum tillage and optimised fertilisation was derived from peer reviewed published studies made outside the region.

The derived shortcomings of our cost-effectiveness analysis mean the results were only indicative of the relative ranking of mitigation practices rather than absolute values and further research is needed to extend the knowledge of the underlying reasons for their implementation. Despite these limitations, the analysis advances our understanding of the cost and the abatement that might be achieved by small changes in crop and soil management which could be used as a complementary tool in mitigation policy development and support.

6.4 Results and Discussion

6.4.1 Representative farming systems and SOC management in Europe

Figure 6.4 provides a broad overview of the farming systems and SOC management that are representative in Europe. The predominant farming systems in EU-27 were field crops, mixed farms and pasture and grasslands. Some exceptions were found in regions of Netherlands with industrial crops or in Spanish and Italian regions with permanent crops. Spain, Denmark, United Kingdom, France and Lithuania showed the regions with the largest agricultural extension in terms of hectares. These regions begin to adopt different combinations of SOC management practices but still have high percentages of conventional tillage (c.a., more than 60% of arable land).

Most of the EU-27 regions showed limited implementation of SOC management practices. The current EU-27 average use of SOC practices in percentage of arable land was: 18% minimum tillage, 7% cover crops, 4% organic farming, 9% residue management, and 86% crop rotation that seems to be the practice most widely undertaken among the European regions. Only Cyprus, Halle region in Germany and Severoiztochen region in Bulgaria were implementing minimum tillage in more than 60% of arable land. None of the regions overcame the 60% of residue management implementation. Cover crops and organic farming were found to be the SOC management practices less implemented for about 7 and 4% of arable land respectively. Salzburg region in Austria and Severozapad region in Czech Republic were exceptions showing higher percentages of organic farming between 20 to 30% of arable land.

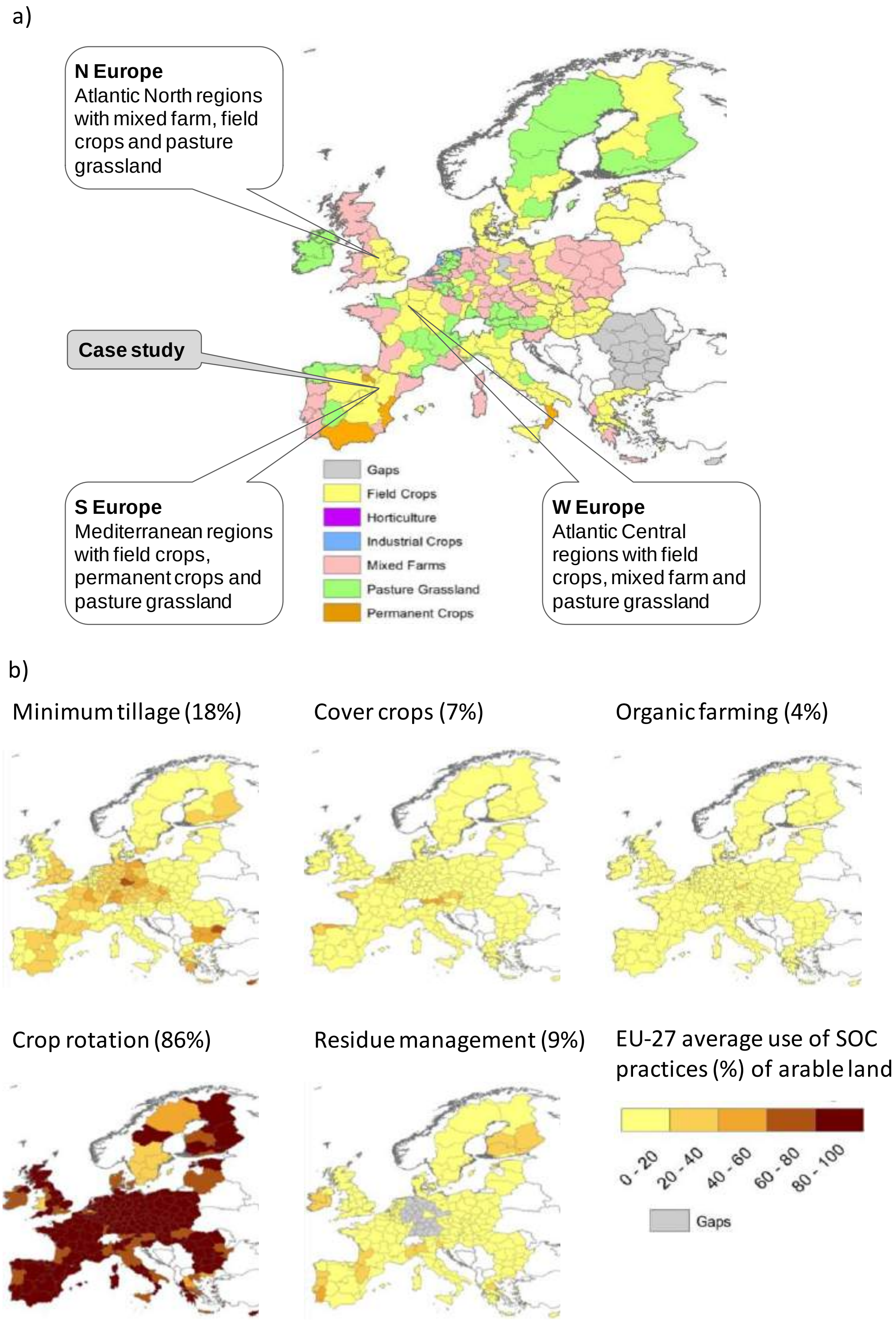


Figure 6.4. (a) representative farming systems in EU-27 regions and for the case study region; (b) the average use of SOC practices (%) of arable land

Our results illustrate the large potential to mitigate anthropogenic CO_2 emissions that have the EU-27 regions by increasing the adoption of SOC management practices.

However, the extent of which farmers are aware of practices that contribute to improve soil carbon (Ingram et al. 2014), the farming systems and the agronomic and climate conditions varies considerably across the European regions. Further studies are necessary to enhance the regional understanding on the effective choices and costs for reducing agricultural emissions. Detailed below are the results of a Mediterranean case study region of South Europe (NE Spain) and its comparison with two Atlantic regions of North and Western Europe covering different farming systems and climate zones in Europe (Figure 6.4).

6.4.2 Abatement potential and costs

The annual abatement potential ($MtCO_2e\ y^{-1}$) and cost (€/$tCO_2e\ ha^{-1}\ y^{-1}$) per mitigation practice by crop type in the case study region are ranked by the MACC in Figure 6.5 and summarized in Table A4.4 (Annex 4). The y-axis in Figure 6.5 represents the reduction in gross margin, therefore measures that are below the x-axis (i.e. negative values) actually indicate an increase in gross margin due to either increased yield or reduced costs. Figure 6.5 shows the annual abatement potential per crop up-scaled for the entire region, and since the practices considered are additive, the cumulative abatement is accounted for as the combined uptake. The MACC illustrates the ranking according to the cost-effectiveness estimation of the marginal increase in SOC by the year.

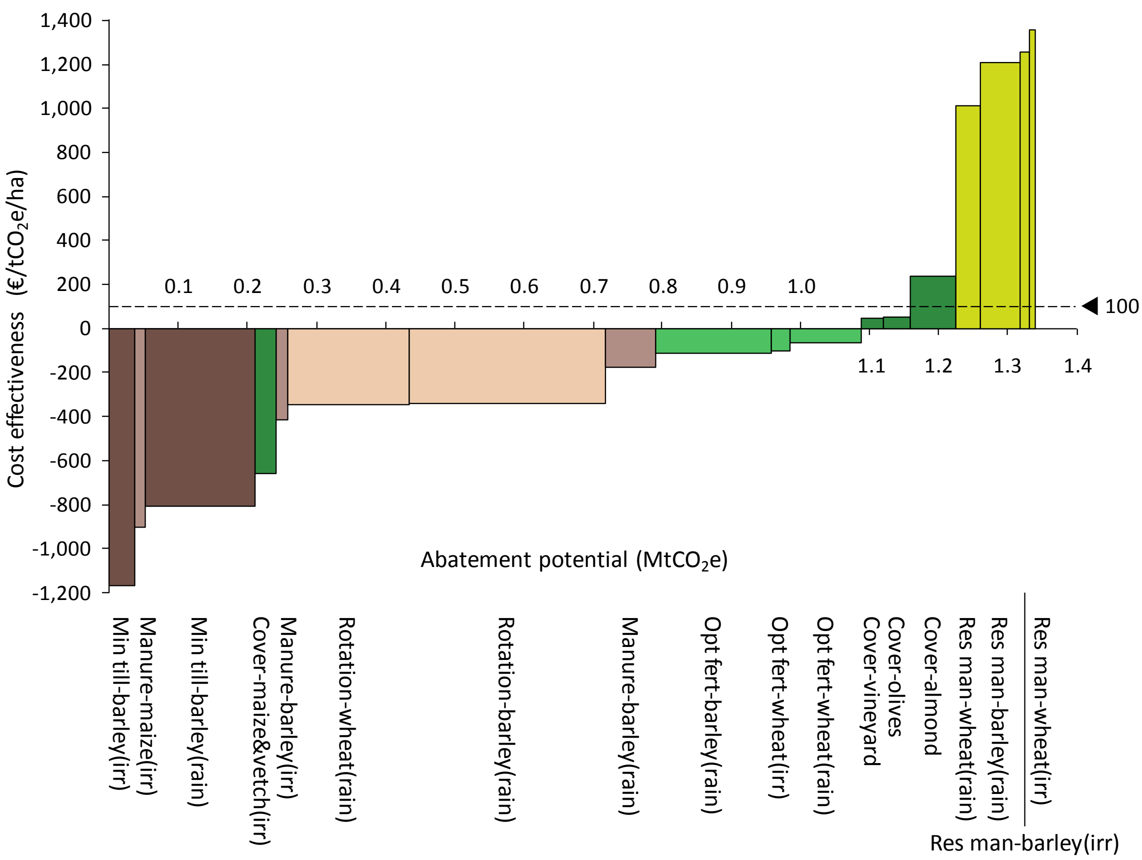


Figure 6.5. MACC for mitigation practices and crops in NE Spain (Aragón region)

The annual abatement potential in the NE Spanish region could range from 1.16MtCO_2e to 1.34MtCO_2e depending on whether the practices implemented are only below (cost-effective practices) or also above (expensive practices) the reference carbon cost of €100/tCO_2e. De Cara and Jayet (2011) estimated the shadow price of carbon to range from 32 to 42€ per tonne of carbon in the EU agriculture sector. Further, Anthoff and Tol (2013) estimated the social cost of carbon by $169 (about €134) per tonne of carbon for regions of the Western Europe. We define the cut off threshold on €100/tCO_2e that is quite concurrent with the shadow price of carbon of £100/tCO_2e applied by MacLeod et al. (2010) and Moran et al. (2011b) to build the MACC for UK agricultural emissions.

The results show that the following mitigation practices might reduce annual emissions by 1.09MtCO_2e at negative or zero costs (i.e. <€0/tCO_2e): (a) Minimum tillage; (b) animal manure fertilization; (c) cover crops in field crops; (d) the inclusion of legumes in rotations; and (e) optimized fertilization. An additional 0.07MtCO_2e can be achieved at a positive cost between 0 and €100/tCO_2e by (f) cover crops in vineyards and olives.

The expensive practices that could provide extra abatements of about 0.18MtCO_2e at positive costs above €100/tCO_2e $ha^{-1}yr^{-1}$ are (g) cover crops in almond and (h) residue management. The complete adoption of the practices could abate about 73% of the total agricultural emissions released by crop cultivation in Aragón. These practices are discussed bellow.

(a) Minimum tillage in barley can provide significant abatements of about 0.2MtCO_2e at the negative cost from -1,168 to -807€/tCO_2e $ha^{-1}yr^{-1}$. Long-term experiments have already proven the potential of these practices to maximize SOC sequestration in the case study area (Álvaro-Fuentes et al. 2014). However, in some regions where every few years the soil need to be cultivated conventionally, the SOC benefit is lost and thus its abatement potential can be overstated (Derpsch et al. 2014; Powlson et al. 2014). Moran et al. (2011b) reported cost findings of about -£1,053/tCO_2e $ha^{-1}yr^{-1}$ for reduced tillage in UK, consistent with our estimations. Pellerin et al. (2013) estimated that these practices would not have significant cost for the farmers in France (c.a. -3 to 12€/tCO_2e $ha^{-1}yr^{-1}$). Minimum tillage has less fuel and time requirements when comparing to conventional tillage. However, experts pointed out agronomic and economic barriers, namely the initial cost of a direct seed-drill and the additional need of spraying might cause low acceptance by farmers, especially for the small sized farms to absorb such costs. Additionally, they noted a strong tradition of conventional tillage practices in the region and an elderly farming population, as reported by Sánchez et al. (2014a).

(b) The costs for manure applied in irrigated maize are about -905 €/tCO_2e $ha^{-1}yr^{-1}$ to achieve abatements of about 0.01MtCO_2e. Irrigated maize in the case study region is grown in an intensive cropping system with high fertilizer requirements and yields can reach up to 14 tonnes/ha (MAGRAMA 2011). This crop has high requirements of N that could be covered from the manure produced by the farmer or bought to surrounding farms at low cost. Manure in barley might also provide abatements of about 0.09MtCO_2e at negative cost from -416 to -177€/tCO_2e $ha^{-1}yr^{-1}$. The use of animal manures is proven to enhance carbon return to the soil (Freibauer et al. 2004). Wang et al. (2014) emphasized the cost-effectiveness of increasing manure to supply about 30% of crop N nutrient in China. MacLeod et al. (2010) also estimated a negative cost of using manure in UK. Experts consulted pointed out that the restrictive legislative requirements for manure management, treatment and transportation may limit its use by many farmers in Spain (EU Nitrates Directive 91/676/EEC). Furthermore availability and cost of manure in areas with low livestock numbers were highlighted as agronomic and economic barriers to its use. The potential impact on surrounding farms and issues with odour for farmers located near to urban areas, were also recognised as social constraints.

(c) Cover crops with irrigated maize can achieve about 0.03MtCO_2e at negative cost from -650 to -400 €/tCO_2e $ha^{-1}yr^{-1}$. Higher yields of intensive irrigated maize can be increased by SOC enhancements from cover crops, since there is no risk of water competition.

(d) The inclusion of legumes in rotations with barley and wheat results in abatements of about 0.46MtCO_2e at the negative cost of -343€/tCO_2e $ha^{-1}yr^{-1}$. Pellerin et al. (2013) found a low positive cost of 19€/tCO_2e $ha^{-1}yr^{-1}$ for legume introduction in crop rotations in France. Lal (2004) reported by meta-analysis that implementing legume-based rotations in semiarid regions may have a positive impact on the SOC pool. However, the expert group noted that including legumes where the annual precipitation is less than 350mm can be unworkable due to crop failure. Further concerns expressed by the expert group included higher costs to control weeds, greater difficulties in selling legumes compared to cereal grains and competition with soybean imports. The discrediting of this practice in the past was also considered a significant barrier for the adoption.

(e) Optimized fertilization in barley and wheat might provide abatements about 0.30MtCO_2e at negative cost about -94€/tCO_2e $ha^{-1}yr^{-1}$. Other studies have shown that adjusting the application rates can be essential to reduce N_2O emissions at negative cost (Moran et al. 2011b; Pellerin et al. 2013; Wang et al. 2014). Experts highlighted agronomic and economic barriers such as the need for infrastructure (e.g. fertigation systems) and the cost entailed in using precise fertilization techniques (e.g. sensors, GPS, software, remote sensing) and soil analysis. However the main uptake barrier identified is the lack of skills and the need for training and capacity building for delivering specific fertilizer recommendations at farm level, this has been noted in other studies (Robert 2002).

(f) Cover crops in rainfed vineyards and olives might provide about 0.07MtCO_2e at a positive cost of about 50€/tCO_2e $ha^{-1}yr^{-1}$. Pellerin et al. (2013) estimated similar costs for farmers in France (c.a. 14€/tCO_2e $ha^{-1}yr^{-1}$). Recent experiments have demonstrated the potential for SOC gains and erosion reduction of cover crops in orchards under semiarid conditions (Marquez-Garcia et al. 2013). Conversely, cover crops can increase costs to the farmer when applied in rainfed systems due to possible water and nutrient competition (Pellerin et al. 2013). Experts identified agronomic and economic barriers, including the risk of decrease in soil moisture, water and nutrient competition between crops and the cost of increased maintenance and management required.

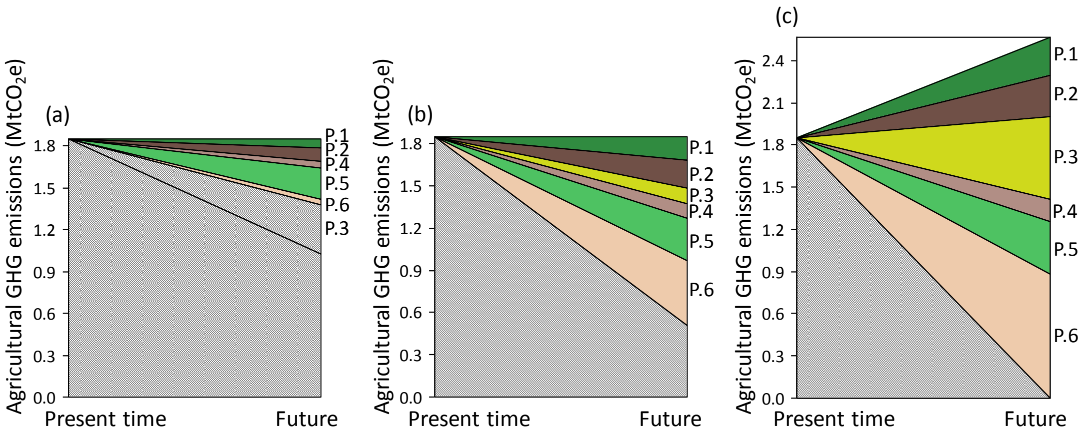
(g) Cover crops in rainfed almonds might provide about 0.06MtCO_2e at a positive cost of 238€/tCO_2e $ha^{-1}yr^{-1}$. The favourable impact of the practice on SOC could make the system more profitable in the long term and an early cover crop removal would minimize possible yield losses (Ramos et al. 2010).

(h) Residue management in barley and wheat could provide abatements about 0.12MtCO_2e at positive cost higher than 100€/tCO_2e $ha^{-1}yr^{-1}$. Higher costs are mainly due to loss of revenue from selling straw for animal feed as a by-product. Wang et al. (2014) found that returning straw or residue back to wheat and maize fields in China, improved soil fertility at a negative cost. Incorporating residues from crops into the soil, where stubble, straw or other crop debris are left on the field, may enhance carbon returns and SOC sequestration (Smith et al. 2008). The expert group reported that there are still some farmers practicing pruning debris burning in the region who do not recognise the need for implementing residue management.

6.4.3 SOC abatement wedges

In terms of the effect of the practices, we show the low, mean and high values for the estimated abatement potentials by SOC abatement wedges. In Figure 6.6 we idealize the SOC improvement as a “ramp” trajectory from the present time – equal to no implementation - to the future – equal to full implementation of practices. The trajectory creates a “potential SOC abatement triangle”, located between the flat trajectory and the ideal SOC trajectory. To keep the focus on practices that have the potential to reduce emissions by improving SOC rather than monetary terms, we plot the SOC triangle into “wedges” that represent the SOC potential of the practices in the case study region.

The results show that both the upper (optimistic) and the lower (pessimistic) levels of estimated mitigation by practices implementation in the region could provide significant abatements. SOC abatement wedges can illustrate the potential role of SOC sequestration by sustainable agricultural management to mitigate emissions. However there is a current discussion on whether to consider the SOC sequestration of agricultural land as a C wedge, since the mitigation potential at global scale can be very limited for the coming decades (Sommer and Bossio 2014; Lassaletta and Aguilera 2015)



(a) Low SOC abatement potential; (b) Mean SOC abatement potential; (c) High SOC abatement potential; P.1 Cover crops; P.2 Minimum tillage; P.3 Residue management; P.4 Animal manure fertilization; P.5 Optimized fertilization; P.6 Crop rotations (with legumes). The barred area shows the agricultural GHG emissions released from crop cultivation in Aragón region

Figure 6.6. Low, mean and high SOC abatement wedges for the mitigation practices in NE Spain (Aragón region)

6.4.4 Farming and policy choices

There is a need to establish priorities to simultaneously reduce emissions and maximize social benefits with a given budget and target commitments (Glenk and Colombo 2011). SOC enhancement practices can provide significant abatements in the European regions and in turn engage farmers as direct financial benefits as reported by our results and in agreement with those of United Kingdom (MacLeod et al. 2010; Moran et al. 2011a), Ireland (O'Brien et al. 2014) and France (Pellerin et al. 2013). According to these results, we have identified four cases in a rationale diagram (Figure 6.7) to determine feasible farming and policy choices. (A) High cost-effectiveness and low annual abatement requires policy options that focus on farmer training and enhanced capacity for efficient and widespread use of these practices. (B) High cost-effectiveness and high annual abatement create optimal conditions, eliminating economic barriers and providing potential for dissemination of and arguably good quality advice on improving or changing management practices. (C) Low cost-effectiveness and low annual abatement correspond to least optimal situation, thereby indicating the need for intervention focus on improving efficiency of crop production and practices implementation through enhanced research and innovation. Finally (D) low cost-effectiveness and high annual abatement requires interventions that focus on direct financial incentives or private payments through offsetting schemes if the social benefits or emissions savings exceed the private costs.

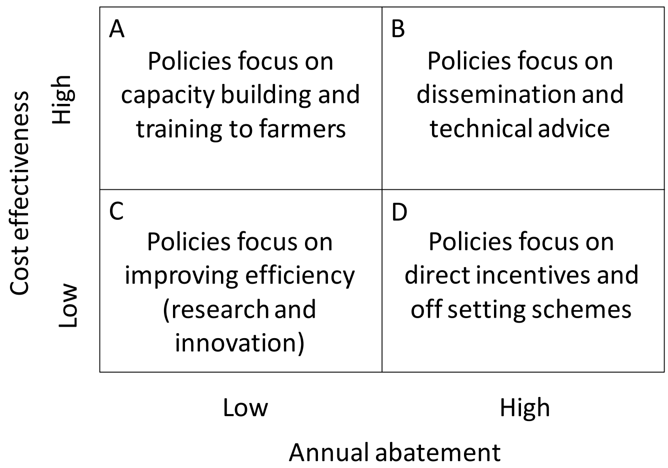


Figure 6.7. Farming and policy choices that can encourage mitigation practices adoption as a result of the combined values of cost-effectiveness and annual abatement potential

However this analysis may be too simplistic since, according to the barriers revealed by the experts in our case study, even when cost effectiveness and abatement are optimal, agronomic and social factors are likely to constrain implementation of promising practices. Some of these constraints may be addressed by policy interventions; for example, training and advisory support can address lack of farmer skills in fertilisation, and capital grants and support can address farmers' need for machinery and additional weed control for minimum tillage. However constraints such as the farmers established traditions of conventional tillage in older communities, poor availability of livestock manure, and unfavourable market conditions for legume crops are more entrenched and beyond the scope of some policy measures.

6.5 Conclusions

Mitigation policies to abate GHG emissions from agriculture need to be renegotiated periodically to take into account the revised results of research. MACC analysis is particularly useful to prioritize mitigation practices and highlight the trade-offs and synergies between economic and environmental effects. However, cost values may be underestimated and abatement potential can be overestimated due to omission of ancillary costs or benefits and current uncertainty on GHG estimations (Kesicki and Strachan 2011; Ward 2014). Therefore, it is important to communicate the underlying assumptions of MACC for their use in mitigation policy development (Kesicki and Ekins 2012). SOC stabilization wedges are useful to understand that each of the wedges represents an effort beyond what would occur under a no-implementation scenario (Pacala and Socolow, 2004). Here we identify a set of agricultural practices that have the capacity to provide abatement while improving land sustainability in Mediterranean regions. Our analysis advances the regional understanding on the cost and the abatement that might be achieved by small changes in crop and soil management. Significant abatements could be achieved at cost below the reference threshold of carbon cost of 100€/tCO_2e (e.g., 1.34 MtCO_2e in NE Spain). Since there is no agreement about which practices to reject, we provide an initial indication of potential farming and policy choices to contribute to mitigation policy at European regional level.

7. Conclusions

7.1 Major findings

This Thesis integrates methods and tools to evaluate potential farming and policy choices to respond to mitigation and adaptation to climate change. The assessment involves both quantitative and qualitative approaches and integrates agronomic, climate and socioeconomic variables at local and regional scale. The multidisciplinary methodology approaches range from the collection of data on previous experimental evidence, to the methodological approaches that integrate farmer behaviour and policy choices (e.g., technology, agricultural management and climate policy). Science-policy integration is one of the most complex challenges that the scientific and policy making communities face since it involves knowledge sharing and ex-change among a wide range of disciplines and actors (Quevauviller et al. 2005).

From the applied methodologies, it is worth noting that the meta-analysis of Chapter 3 comprises an original literature review on the effect of temperature on crops of around 140 peer reviewed articles including results of experiments dating from 1914. The methodological framework of Chapter 4 combines a water availability model under different policy choices scenarios (i.e., WAAPA model) and a participatory data collection process (i.e., semi-structured interviews) to assess impacts of climate change and flexible adaptation options for agricultural water management. Further, in Chapter 5 two methods that include the stakeholders' involvement (i.e., multi-criteria analysis with experts and logistic and Poisson regression models of farmer surveys) are used to assess mitigation farming practices and their adoption barriers. Finally, in Chapter 6, science-base policy tools (i.e., marginal abatement cost curves and SOC abatement wedges) help to illustrate the mitigation potential and cost of the selected farming practices in Chapter 5.

Overall, the results of this Thesis provide information to adapt to, and mitigate of, climate change at farm level to support the development of a comprehensive climate policy and to assist farmers. The findings show the key temperature thresholds and response to extreme temperature effects for rice, maize and wheat, so such responses can be included into crop impact and adaptation models. A portfolio of flexible adaptation and mitigation choices at local scale are identified. The results also provide a better understanding of the stakeholders oppose or support to adopt the choices which could be used to incorporate in local adaptation plans and mitigation regional policy. The findings include estimations for the farming and policy choices on the capacity to improve water supply reliability, abatement potential and cost-effective in Mediterranean regions.

7.1.1 Crop response to extreme temperature

There is a limit to the extent that crop simulation models, used to predict yields, model responses to extreme temperatures. This Thesis provides a meta-analysis of existing data in which the cardinal temperatures are identified for important processes in maize and rice (Chapter 3). This study tries to complete the analysis started by Porter and Gawith (1999) for wheat for the three major global cereals (i.e., rice, maize and wheat). It also adds a comparison for wheat so that within a single study a reader can get this information on the three main cereals. The findings show the key temperature thresholds and response to extreme temperature effects for rice, maize and wheat, so such responses can be included into crop impact and adaptation models. Lethal temperatures and cardinal temperatures, together with error estimates, have been identified for phenological phases and development stages.

The results show that cardinal temperatures are conservative between studies and are seemingly well-defined in all three crops. The main findings with relevance to climate change are that maximum lethal temperatures are similar for the three crops and range from 43ºC to 48ºC. Standard lethal temperature errors for rice and wheat are small and higher (2.9ºC) in maize, probably due to maize is planted over the widest range of latitude. Minimum lethal temperatures differ in a broad range, showing that wheat has the lowest average minimum (-17.2ºC); maize dies at temperatures just below freezing and rice at temperatures under 5ºC. Again, the largest standard error (1.9ºC) is in maize.

Anthesis and ripening are especially important for yields of the three main global cereals and in turn the most sensitive temperature stages. Maize and rice are very sensitive to the same maximum temperature (ca. 37ºC) with similar small standard errors around anthesis; wheat has a lower maximum (ca. 32ºC). The reduction in grain set caused by overstepping these thresholds can be dramatic (Wheeler et al., 1996a) and all three crops can suffer large yield losses due to sterility at high extreme temperatures. Maximum grain-filling temperatures are lower for rice (31.3ºC) than for maize and wheat (36ºC and 35.4ºC respectively) and are all well-defined. The minimum rice temperature for grain filling is markedly higher than for maize and wheat. The largest temperature response variation appears on the optimum temperature with the higher standard errors for all the crops, although maize also shows a high standard error of minimum temperature.

An important point on crop temperature responses is that we are dealing with absolute and not relative thresholds; that is to say moving temperature above a given level induces non-linear responses from plants that are not evident if temperatures remain in the range below or above the threshold. Thresholds do not seem to be defined in terms of a relative change in temperature (ie. a ‘delta’) but as step changes in plant development and thereby growth. Such threshold responses are not often included in the current suite of statistical and process-based crop models used to analyse and predict the effects of global warming on crop production. As a result, ensembles of crop models are able to predict mean yields (Rötter et al., 2011) but do less well when predicting yield variability and thus are likely too optimistic when predicting the effects of warming.

These findings are expected to be helpful for new crop impact and adaptation models in combination with new scenarios (RCPs) and climate data series.

7.1.2 Adaptation farm and policy choices

In the Lower Guadalquivir River Basin District, existing water conflicts between the rice farming and the natural ecosystem are expected to be intensified in the future due to projected scenarios of water availability reduction (WAAPA model) and higher temperatures (overstepping temperature threshold for rice as reported in Chapter 3). The intensive water management required to produce rice in the Doñana coastal wetland (a world heritage and biodiversity site) stands at a crucial point since freshwater supply is deteriorating at an unprecedented rate. This Thesis (Chapter 4) explores flexible adaptation options presenting an approach that assesses how – water policy and local actors – may influence water in the costal wetland under climate change. Together, policy and stakeholder choices are useful in singling out areas for moving towards adaptation and dialogue.

The findings show that reductions of water runoff and increased variability, resulting from exposure to climate change, will lead to significant decreases in the water availability. The simulations of water availability changes in all sub-basins range from -45 to -93% of current water availability. Further, the irrigation demand is expected to increase due to decreases in effective rainfall and increase in potential evapotranspiration (due to higher temperature and changes of other meteorological variables). Hence, four adaptation policy scenarios are constructed aiming to maintain adequate water reliability for urban, ecosystem and irrigation demands in the region. The effect of the adaptation effort is estimated from the difference between water availability for irrigation in the control and in the climate change scenario. The Adaptation Policy 1 addressed to improve water urban use could reach major improvements of water availability for irrigation and in turn avoid reduced water for environmental use by adaptation policy 2. The use of additional water infrastructure for irrigation (e.g. from hydropower reservoirs) was performed by the adaptation policy 3. The simulations showed that the effect for improving water availability of policy 3 was not significant. Adaptation options to improve the water managements by interconnections (a new pipeline connecting upstream water bodies to the rice fields, additional releases from upstream reservoirs or transfer of water) were endorsed into adaptation policy 4. The adoption of policy 4 was specially controversy between stakeholders in their acceptance, however the simulations clearly showed improvement of less than 20% except in a few sub-basins and scenarios.

A portfolio of adaptation options for water resources management seem to be rather than seeking consensus on the "best" option or process. These adaptation options are framed according to the local environmental, social and policy context from the integration of stakeholder choices and potential policy choices. The results conclude that there is a need of flexible and adaptive institutional regimes, social research and public participation, and improved monitoring and mechanisms for information exchange among others, which seem to be quite concurrent with similar studies (Cohen et al. 2006; Tisdell 2010; Méndez et al. 2012). The findings also suggest that the perception on new water infrastructure and farming subsidies dominates the decision process.

Climate change is a global challenge with increasing severe consequences at the local level. This information may be used to develop climate policy and up-scale to other Mediterranean regions for water management and sustainable rice faming.

7.1.3 Mitigation farm and policy choices

The reductions of agricultural emissions to achieve the EU targets depend on the quantitative details of mitigation potential and cost of the management at the farm level, the barriers to behavioural change and the agricultural policy that influences farmers' decisions (Smith et al. 2007a; Stern 2007; OECD 2012b). Among the agricultural practices that can contribute to reaching EU targets, the management of agricultural soils has a large mitigation potential with proven benefits for farmers and the environment. This Thesis evaluates the implementation, the barriers to adoption, the abatement potential and the cost effectiveness of these practices at the farm level (Chapter 5 and Chapter 6). The study area is a representative region in NE Spain (Aragón) that exemplifies semiarid Mediterranean agricultural systems.

The findings show that small changes in agricultural practices have a large potential for reducing greenhouse gas emissions (e.g. cover crops in field and tree crops, minimum tillage, residue management, manure fertilization, optimized fertilization, crop rotations with legumes). However, the implementation of such practices at the local level is often limited by a range of barriers, like climatic constraints (e.g., limiting precipitation threshold for applying rotations with legumes in arid areas), agronomic constraints (e.g., the possible water and nutrients competition between crops in rainfed systems with cover crops), and social constraints (e.g., strong traditions or acceptance). Understanding the barriers is essential for defining effective measures, the actual mitigation potential of the measures, and the policy needs to ensure implementation. Results show that farmers' environmental concerns, financial incentives and access to technical advice are the main factors that define their barriers to implementation. Further the results show that these practices can be financially attractive for

Mediterranean farmers. Significant abatements could be achieved at cost below the reference threshold of carbon cost of 100€/tCO_2e (1.34 MtCO_2e in the case study region).

The dissemination of scientific advances, technical information and agricultural policies relating to these mitigation practices will play an important role in encouraging the agricultural population to adopt. According to the barriers revealed in the case study, even when cost effectiveness and abatement are optimal, agronomic and social factors are likely to constrain implementation of promising practices. Some of these constraints may be addressed by policy interventions; for example, training and advisory support can address lack of farmer skills in fertilisation, and capital grants and support can address farmers' need for machinery and additional weed control for minimum tillage. However constraints such as the farmers established traditions of conventional tillage in older communities, poor availability of livestock manure, and unfavourable market conditions for legume crops are more entrenched and beyond the scope of some policy measures.

In view of these results, a series of Factsheets adapted to different Spanish farming systems has been also developed to support novel farmer adoption of these mitigation practices (see Annex 5). The factsheets presents lessons learned from real life case studies to exemplify the implementation of neighbouring farmers that have benefits and positive results.

These local results may be also up-scaled to other European regions with similar farming systems and conditions where the implementation is still low. They can further contribute to develop effective mitigation policy to be included in the 2020 review of the European Union Common Agricultural Policy.

7.2 Research contributions

7.2.1 Methods

From the methodological approach this Thesis provides the following contributions:

- Developing a complete meta-analysis (ca. 140 peer reviewed articles) of existing experimental evidence on the effect of temperature on the three major crops (i.e., rice, maize and wheat) to provide needed inputs for future crop impact and adaptation models.
- Proposing a methodological framework by combining a water availability model and a participatory data collection process to integrate stakeholder and policy choices. This methodological framework can provide realism and valuable results to the adoption of a local adaptation strategy.
- Proposing a methodology by combining a multi-criteria analysis and logistic and Poisson regression models to prioritize mitigation farming practices under climate scenarios and assess the potential implementation and barriers.
- Developing a methodology approach based on science-base policy tools (i.e., marginal abatement cost curves and SOC abatement wedges) to illustrate the mitigation potential and cost effectiveness of mitigation farming practices. This methodology is strengthened suggesting a rationale diagram to determine feasible farming and policy choices according to the obtained results.

7.2.2 Results and practical application of the research

From the perspective of the results this Thesis provides the following contributions:

- Providing an original and extensive database that includes the mean lethal and cardinal temperatures together with error estimates, for the most important processes, phenological phases and development stages in maize and rice. A comparison for wheat is included to easily get the information on the three main cereals.
- Providing a portfolio of flexible adaptation choices that aims to improve the water supply reliability for rice production, livelihood support and the environment at local scale. This study also provides increased comprehension of

the stakeholders oppose or support to the adaptation choices which could be used to incorporate in local adaptation plans.

- Identifying a set of agricultural practices which can result in an optimized balance between crop productivity and mitigation potential in a semi-arid region in the Mediterranean. Providing information on the barriers to the implementation of these practices to address the policy interventions that encourage the adoption. Developing a series of Factsheets adapted to different Spanish farming systems to support novel farmer adoption of these mitigation practices

- Providing information on cost-effective and abatement potential of mitigation practices to support policy makers to reach mitigation targets and facilitate farmers to select the most appropriate practices for Mediterranean farming systems.

7.2.3 Limitations and future research

This Thesis represents an attempt to explore the potential farming and policy choices to respond to climate change. Different agronomic and socio-economic aspects have been studied and interesting results arise. However, there are some limitations or paths for future research:

- The differences in conditions between experiments identified in this Thesis, call for experimental designs that have all three crops simultaneously monitored under the same controlled environmental conditions. Further experimental studies of the effect of transgressing threshold temperatures so such responses can be included into crop impact and adaptation models

- In this Thesis several farming and policy choices have been assessed for mitigation of, and adaptation to, climate change in agriculture. However, further analysis about the synergies and trade-offs between the two climate policy interventions need to be undertaken.

- The assessment presented in this Thesis attempt to integrate farmer behaviour and policy choices (e.g., technology, agricultural management and climate policy). Different assumptions for the proposed models and tools could be further studied as well as to increase the participation of stakeholders to provide realism into the policy making process.

- In this thesis, the potential of farming and policy choices to respond to climate change has been assessed at local and regional level. Similar analysis could be applied to different agricultural areas and at national scale. The development of learning and demonstration studies that involve the practitioners need to be extended to increase the adoption rates.

References

Aguilar M (2010) Producción integrada del arroz en el sur de España. Consejería de Agricultura y Pesca. ISBN 978-84-8474-290-6. Junta de Andalucía, pp. 320

Aguilera E, Lassaletta, L, Gattinger A, Gimeno BS (2013) Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. Agriculture, Ecosystems & Environment, 168, 25-36

Alcamo J, Döll P, Henrichs T, Kaspar F, Lehner B, Rösch T, Siebert S (2003) Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions. Hydrological Sciences Journal, 48(3), 339-348

Alcamo J, Olesen JE (2012) Life in Europe under climate change, Wiley Blackwell, Chichester, UK

Álvaro-Fuentes J, Cantero-Martínez C (2010) Potential to mitigate anthropogenic CO_2 emissions by tillage reduction in dryland soils of Spain. Spanish Journal of Agricultural Research, 8(4), 1271-1276

Álvaro-Fuentes J, Easter M, Cantero-Martínez C, Paustian K (2011) Modelling soil organic carbon stocks and their changes in the northeast of Spain. European Journal of Soil Science, 62(5), 685-695

Álvaro-Fuentes J, Paustian K (2011) Potential soil carbon sequestration in a semiarid Mediterranean agroecosystem under climate change: Quantifying management and climate effects. Plant and Soil, 338 (1-2), 261-272

Álvaro-Fuentes J, Plaza-Bonilla D, Arrúe JL, Lampurlanés J, Cantero-Martínez C (2014) Soil organic carbon storage in a no-tillage chronosequence under Mediterranean conditions. Plant and Soil, 376(1-2), 31-41

Andersen E (2010) Regional typologies of farming systems contexts, SEAMLESS Report no. 53, SEAMLESS integrated project, www.SEAMLESS-IP.org, pp. 41, ISBN no. 978-90-8585-596-5

Anthoff D, Tol RSJ (2013) The uncertainty about the social cost of carbon: a decomposition analysis using FUND. Climatic Change, 117(3), 515-530

Antle JM, Capalbo SM, Mooney S, Elliott ET, Paustian KH (2001) Economic analysis of agricultural soil carbon sequestration: an integrated assessment approach. Journal of Agricultural and Resource Economics, 344-367

Archie KM (2013) Mountain communities and climate change adaptation: barriers to planning and hurdles to implementation in the Southern Rocky Mountain Region of North America. Mitigation and adaptation strategies for global change, 19(5), 569-587

Arnold CY (1974) Predicting stages of sweet corn (Zea mays L.) development. Journal of the American Society for Horticultural Science, 99, 501–505.

Badía D (2011) iARASOL, programa interactivo para el estudio y clasificación de suelos de Aragón. http://www.suelosdearagon.com/

Baker JT (2004) Yield responses of southern US rice cultivars to CO_2 and temperature. Agricultural and Forest Meteorology, 122(3), 129-137

Bale JS, Masters GJ, Hodkinson ID, Awmack C, Bezemer TM, Brown VK., Butterfield J, Buse A, Coulson JC, Farrar J, Good JEG, Harrington R, Hartley S, Jones TH, Lindroth RL, Press MC, Symrnioudis I, Watt AD, Whittaker JB (2002) Herbivory in global climate change research: direct effects of rising temperature on insect herbivores. Global Change Biology, 8(1), 1-16

Bardají I, Iglesias A (2014) Mitigación y adaptación al cambio climático. Perspectivas políticas y la nueva PAC. In: Bardají (Eds.) Reflexiones en torno a la PAC. Cajamar Caja Rural. Serie Economía 22

Bardají I, Iraizoz B (2015) Uneven responses to climate and market influencing the geography of high-quality wine production in Europe. Regional Environmental Change, 15(1), 79-92

Barnabás B, Jäger K, Fehér A (2008) The effect of drought and heat stress on reproductive processes in cereals. Plant, Cell & Environment, 31(1), 11-38

Beaumont NJ, Tinch R (2004) Abatement cost curves: a viable management tool for enabling the achievement of win–win waste reduction strategies? Journal of Environmental Management, 71(3), 207-215

Beniston M, Stephenson DB (2004) Extreme climatic events and their evolution under changing climatic conditions. Global and Planetary Change, 44(1), 1-9

Berbel J, Mesa-Jurado MA, Pistón JM (2011) Value of irrigation water in Guadalquivir basin (Spain) by residual value method. Water Resources Management, 25(6), 1565-1579

Berrang-Ford L, Ford JD, Lesnikowski A, Poutiainen C, Barrera M, Heymann SJ (2014) What drives national adaptation? A global assessment. Climatic Change, 1-10

Biesbroek GR, Swart RJ, Carter TR, Cowan C, Henrichs T, Mela H, Morecroft MD, Rey D (2010) Europe adapts to climate change: comparing national adaptation strategies. Global Environmental Change, 20(3), 440-450

Birch CJ, Andrieu B, Fournier C (2002) Dynamics of internode and stem elongation in three cultivars of maize. Agronomie, 22(5), 511-524.

Birch CJ, Hammer GL, Rickert KG (1998a) Temperature and photoperiod sensitivity of development in five cultivars of maize (Zea mays L.) from emergence to tassel initiation. Field Crops Research, 55(1), 93-107

Birch CJ, Hammer GL, Rickert KG (1998b) Modelling leaf production and crop development in maize (Zea mays L.) after tassel initiation under diverse conditions of temperature and photoperiod. Field Crops Research, 58(2), 81-95

Blanco-Gutiérrez I, Varela-Ortega C, Purkey DR (2013) Integrated assessment of policy interventions for promoting sustainable irrigation in semi-arid environments: A hydro-economic modeling approach. Journal of Environmental Management, 128, 144-160

Bockel L, Sutter P, Touchemoulin O, Jönsson M (2012) Using marginal abatement cost curves to realize the economic appraisal of climate smart agriculture policy options. FAO, Rome, EasyPol Module 116, pp. 36

Böhringer C, Rutherford TF, Tol RSJ (2009) The EU 20/20/2020 targets: An overview of the EMF22 assessment. Energy Economics, 31, S268-S273

Bracht J, Figuières C, Ratto M (2008) Relative performance of two simple incentive mechanisms in a public goods experiment. Journal of Public Economics, 92(1), 54-90

Breidenich C, Magraw D, Rowley A, Rubin JW (1998) The Kyoto protocol to the United Nations framework convention on climate change. American Journal of International Law, 315-331

Brooking IR (1990) Maize ear moisture during grain-filling and its relation to physiological maturity and grain-drying. Field Crops Research, 23(1), 55-68

Brooking IR (1993) Effect of temperature on kernel growth rate of maize grown in a temperate marine environment. Filed crop Research, 35(2), 135-145

Brown RA, Rosenberg NJ (1997) Sensitivity of crop yield and water use to change in a range of climatic factors and CO_2 concentrations: a simulation study applying EPIC to the central USA. Agricultural and Forest Meteorology, 83(3), 171-203

Bryan E, Deressa TT, Gbetibouo GA, Ringler C (2009) Adaptation to climate change in Ethiopia and South Africa: options and constraints. Environmental Science & Policy, 12(4), 413-426

Bryson JM (2004) What to do when stakeholders matter: stakeholder identification and analysis techniques. Public Management Review, 6(1), 21-53

Burton I, Huq S, Lim B, Pilifosova O, Schipper EL (2002) From impacts assessment to adaptation priorities: the shaping of adaptation policy. Climate Policy, 2(2-3), 145-159

Buse A (1982) The likelihood ratio, Wald and Lagrange multiplier tests: an expository note. The American Statistician, 36(3a), 153-157

Cameron AC, Trivedi PK (1986) Econometric models based on count data. Comparisons and applications of some estimators and tests. Journal of Applied Economics, 1(1), 29-53

Cameron AC, Trivedi PK (2005) Microeconometrics: Methods and Applications. Cambridge University Press, New York

Carberry PS, Muchow RC, McCown RL (1989) Testing the CERES-maize simulation model in a semi-arid tropical environment. Field Crops Research, 20(4), 297-315

Carlsen B, Glenton C (2011). What about N? A methodological study of sample-size reporting in focus group studies. BMC Medical Research Methodology, 11(1), 26

Carter PR, Hesterman OB (1990) Handling corn damage by autumn frost. Purdue University Cooperative Extension Service Climate & Weather. www.ces.purdue.edu

Cary JW, Webb T, Barr NF (2001) The adoption of sustainable practices: Some new insights. An analysis of drivers and constraints for the adoption of sustainable practices derived from research. Land and Water Australia, Canberra

CEDEX (2011) Evaluación del impacto del cambio climático en los recursos hídricos en régimen natural [Evaluation of the impact of climate change in water resources under natural regime]. Centre of Public Works Studies and Experimentation, CEDEX, Madrid, Spain

Challinor AJ, Wheeler TR, Craufurd PQ, Ferro CAT, Stephenson DB (2007) Adaptation of crops to climate change through genotypic responses to mean and extreme temperatures. Agriculture, Ecosystems & Environment, 119(1), 190-204

Chaudhary TN, Ghildyal BP (1969) Germination response of rice seeds to constant and alternating temperatures. Agronomy Journal, 61(2), 328-330

Chaudhary TN, Ghildyal BP (1970a) Effect of temperature associated with levels of bulk density on rice seedling emergence. Plant and Soil, 33(1-3), 87-91

Chaudhary TN, Ghildyal BP (1970b) Influence of submerged soil temperature regimes on growth, yield, and nutrient composition of rice plant. Agronomy Journal, 62(2), 281-285

CHE (2014) Plan Hidrológico de la demarcación hidrográfica del Ebro, aprobado por Real Decreto 129/2014. Ebro Hydrologic Basin Authority, Spanish Ministry of the Environment, Madrid. Available online at: www.chebro.es

CHG (2013) Plan Hidrológico de la demarcación hidrográfica del Guadalquivir, aprobado por Real Decreto 355/2013. Guadalquivir Hydrologic Basin Authority, Spanish Ministry of the Environment, Madrid. Available online at: www.chguadalquivir.es

Cohen S, Neilson D, Smith S, Neale T, Taylor B, Barton M, Merritt W, Alila Y, Shepherd P, Mcneill R, Tansey J, Carmichael J, Langsdale S (2006) Learning with local help: expanding the dialogue on climate change and water management in the Okanagan region, British Columbia, Canada. Climatic Change, 75(3), 331–358

Cossins AR, Bowler K (1987) Temperature biology of animals. Chapman and Hall, New York.

Crowley JG (1998) Improving the yield and quality of forage maize. End of project report. Teagasc, Oak Park, Carlow, Ireland, pp. 10

Cummings JL, Doh J (2000) Identifying who matters: mapping key players in multiple environments. California Management Review, 42(2), 83-104

Czaja R, Blair J, (2005) Designing Surveys: A Guide to Decisions and Procedures, 2nd edn. Sage Publications, Thousand Oaks

De Cara S, Jayet PA (2011) Marginal abatement costs of greenhouse gas emissions from European agriculture, cost effectiveness, and the EU non-ETS burden sharing agreement. Ecological Economics, 70(9), 1680-1690

De Leeuw ED (2005) To mix or not to mix data collection modes in surveys. Journal of Official Statistics Stockholm, 21(2), 233-255

De Stefano L, Hernandez Mora N, Iglesias A, Sánchez B (2014) Water for rice farming and biodiversity: exploring choices for adaptation to climate change in Doñana, southern Spain. In: Stucker D and Lopez-Gun E (eds) Adaptation to Climate Change through Water Resources Management: Capacity, Equity, and Sustainability. Oxford, UK, Routledge / Earthscan

Del Grosso SJ, Cavigelli MA (2012) Climate stabilization wedges revisited: can agricultural production and greenhouse-gas reduction goals be accomplished? Frontiers in Ecology and the Environment, 10(10), 571-57

Derpsch R, Franzluebbers AJ, Duiker SW, Reicosky DC, Koeller K, Friedrich T, Sturny WG, Sá JCM, Weiss K (2014) Why do we need to standardize no-tillage research? Soil and Tillage Research, 137, 16-22

Dingkuhn M, Sow A, Samb A, Diack S, Asch F (1995) Climatic determinants of irrigated rice performance in the Sahel I. Photothermal and micro-climatic responses of flowering. Agricultural Systems, 48(4), 385-410

Döll P, Hauschild M (2002) Model-based regional assessment of water use: an example for Northeastern Brazil. Water International, 27(3), 310-320

Domínguez IP, Fellmann T (2015) The need for comprehensive climate change mitigation policies in European agriculture. EuroChoices, 14(1), 11-16

Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO (2000) Climate extremes: observations, modeling, and impacts. Science, 289(5487), 2068-2074

EC (2009a) Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020. Official Journal of the European Union, L140, 136-148

EC (2009b) The role of European agriculture in climate change mitigation. Commission Staff Working Document Nº 1093. Final Commission of the European Communities, Brussels

EC (2013a) Commission decision of 26 March 2013 on determining Member States' annual emission allocations for the period from 2013 to 2020 pursuant to Decision No 406/2009/EC of the European Parliament and of the Council (2013/162/EU). Official Journal of the European Union, L90, 106-110

EC (2013b) Decision No 529/2013/EU of the European Parliament and of the Council of 21 May 2013 on accounting rules on greenhouse gas emissions and removals resulting from activities relating to land use, land-use change and forestry and on information concerning actions relating to those activities. Official Journal of the European Union, L165, 80-97

Eden C, Ackermann F (1998) Analysing and comparing idiographic causal maps. Managerial and organisational cognition. Theory Method and Research, 192-209

EEA (2010) The European environment, State and outlook 2010. State of the environment report. European Environment Agency, Copenhagen

EEA (2012) European waters - current status and future challenges. Synthesis Report No 9/2012. European Environment Agency, Copenhagen, pp. 52

Ehrler W, Bernstein L (1958) Effects of root temperature, mineral nutrition, and salinity on the growth and composition of rice. Botanical Gazette, 120, 67-74

Ellis RH, Qi A, Summerfield RJ, Edmeades GO, Roberts EH (1992) Photoperiod, temperature, and the interval from sowing to tassel initiation in diverse cultivars of maize. Crop Science, 32(5), 1225-1232

Ellis RH, Qi A, Summerfield RJ, Roberts EH (1993) Rates of leaf appearance and panicle development in rice (Oryza sativa L.): a comparison at three temperatures. Agricultural and Forest Meteorology, 66(3), 129-138

Enomoto N, Yamada I, Hozumi K (1956) On the artificial germination of pollen in rice plants. Temperature limits of pollen germination in rice varieties. Proceedings of the Crop Science Society of Japan, 25(2), 69-70

Eurobarometer Surveys on Climate Change (2011) European's attitudes towards climate change. http://ec.europa.eu/public_opinion/archives/ebs/ebs_372_en.pdf

EUROSTAT (2013) Database. Structure of agricultural holdings in 2010

Ewert F, Rounsevell MDA, Reginster I, Metzger MJ, Leemans R (2005) Future scenarios of European agricultural land use: I. Estimating changes in crop productivity. Agriculture, Ecosystems & Environment, 107(2), 101-116

Fadzillah NM, Gill V, Finch RP, Burdon RH (1996) Chilling, oxidative stress and antioxidant responses in shoot cultures of rice. Planta, 199(4), 552-556

Feder G, Umali DL (1993) The adoption of agricultural innovations: a review. Technological Forecasting and Social Change, 43(3), 215-239

Fernández FJ, Blanco M (2015) Modelling the economic impacts of climate change on global and European agriculture. Review of economic structural approaches. Economics: The Open-Access, Open-Assessment E-Journal, 9(2015-10), 1-53

Fischer G, Shah M, Tubiello FN, van Velhuizen H (2005) Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. Philosophical Transactions of the Royal Society B: Biological Sciences, 360(1463), 2067-2083

Fischer RA (2011) Wheat physiology: a review of recent developments. Crop Pasture Science, 62, 95-114

Follet RF (2001) Soil management concepts and carbon sequestration in croplands soils. Soil and Tillage Research, 61(1), 77-92

Fournier C, Andrieu B (1998) A 3D architectural and process-based model of maize development. Annals of Botany, 81(2), 233-250

Freeman RE (1984) Strategic management: A stakeholder approach. Cambridge University Press

Freibauer A, Rounsevell MD, Smith P, Verhagen J (2004) Carbon sequestration in the agricultural soils of Europe. Geoderma, 122(1), 1-23

Füssel HM, Klein RJ (2006) Climate change vulnerability assessments: an evolution of conceptual thinking. Climatic Change, 75(3), 301-329

Gao L, Jin Z, Huang Y, Zhang L (1992) Rice clock model: computer model to simulate rice development. Agricultural and Forest Meteorology, 60(1), 1-16

García de Jalón S, Iglesias A, Quiroga S, Bardají I (2013) Exploring public support for climate change adaptation policies in the Mediterranean region: A case study in Southern Spain. Environmental Science & Policy, 29, 1-11

García Novo F, Marín Cabrera C (2006) Doñana: water and biosphere, Doñana 2005 Project. Guadalquivir Hydrologic Basin Authority, Spanish Ministry of the Environment, Madrid

García-Llorente M, Martín-López B, Montes C (2011) Exploring the motivations of protesters in contingent valuation: insights for conservation policies. Environmental Science & Policy, 14(1), 76-88

Garrick D, Siebentritt MA, Aylward B, Bauer CJ, Purkey A (2009) Water markets and freshwater ecosystem services: Policy reform and implementation in the Columbia and Murray-Darling Basins. Ecological Economics, 69(2), 366-379

Garrote L, Iglesias A, Granados A, Mediero L, Martín-Carrasco F (2015) Quantitative assessment of climate change vulnerability of irrigation demands in Mediterranean Europe. Water Resources Management, 29(2), 325-338

Garrote L, Iglesias A, Martín-Carrasco F, Mediero L (2011) WAAPA: A model for water availability and climate change adaptation policy analysis. Proceedings of the VI EWRA International. Symposium - Water Engineering and Management in a Changing Environment, Catania

Georgopoulou E, Sarafidis Y, Mirasgedis S, Zaimi S, Lalas DP (2003) A multiple criteria decision-aid approach in defining national priorities for greenhouse gases emissions reduction in the energy sector. European Journal of Operational Research, 146(1), 199-215

Glenk K, Colombo S (2011) Designing policies to mitigate the agricultural contribution to climate change: an assessment of soil based carbon sequestration and its ancillary effects. Climatic Change, 105(1-2), 43-66

Glicken J (2000) Getting stakeholder participation 'right': a discussion of participatory processes and possible pitfalls. Environmental Science & Policy, 3(6), 305-310

Gonzalez-Zeas D, Garrote L, Iglesias A, Sordo-Ward A (2012) Improving runoff estimates from regional climate models: a performance analysis in Spain. Hydrology and Earth System Science, 16(6), 1709–1723

Gujarati D, Porter D (2009) Basic Econometrics, 5th edn. McGraw-Hill Irwin, New York

Hamdani AR (1979) Low-temperature problems and cold tolerance research activities for rice in India. In: Report of a rice cold tolerance workshop. International Rice Research Institute, Los Baños, Philippines, pp. 39-48

Han F, Chen H, Li X, Yang M, Liu G, Shen S (2009) A comparative proteomic analysis of rice seedlings under various high-temperature stresses. Biochimica Et Biophysica Acta, 1794, 1625-1634

Hanak E, Lund JR (2012) Adapting California's water management to climate change. Climatic change, 111(1), 17-44

Hanemann M, Labandeira X, Loureiro M (2011) Climate change, energy and social preferences on policies: exploratory evidence for Spain. Climate Research, 48(2), 343-348

Hansen J, Kharecha P, Sato M, Masson-Delmotte V, Ackerman F, Beerling DJ, Hearty PJ, Hoegh-Guldberg O, Hsu SL, Parmesan C, Rockstrom J, Rohling EJ, Sachs J, Smith P, Steffen k, Susteren LV, Schuckmann KV, Zachos JC (2013) Assessing "dangerous climate change": required reduction of carbon emissions to protect young people, future generations and nature. PLoS ONE 8(12): e81648. doi:10.1371/journal.pone.0081648

Harrell MC, Bradley MA (2009) Data collection methods. Semi-structured interviews and focus groups. Rand National Defense Research Institute, Santa Monica

Hawkins E, Fricker TE, Challinor AJ, Ferro CAT, Ho CK, Osborne TM (2012) Increasing influence of heat stress on French maize yields from the 1960s to the 2030s. Global Change Biology, 19(3), 937-947

Hellerstein D, Nickerson C, Cooper J, Feather P, Gadsby D, Mullarkey D, Tegene A, Barnard C (2002) Farmland protection: The role of public preferences for rural amenities. USDA Economic Research Service, Agricultural Economic Report No. 815

Herath W, Ormrod DP (1965) Some effects of water temperature on the growth and development of rice seedlings. Agronomy Journal, 57(4), 373-376

Herrero J, Snyder RL (1997) Aridity and irrigation in Aragon, Spain. Journal of Arid Environments, 35(3): 535-547

Herrero MP, Johnson RR (1980) High temperature stress and pollen viability in maize. Crop Science, 20(6), 796-800

Howden SM, Soussana JF, Tubiello FN, Chhetri N, Dunlop M, Meinke H (2007) Adapting agriculture to climate change. Proceedings of the National Academy of Sciences, 104(50), 19691-19696

Hund A, Fracheboud Y, Soldati A, Stamp P (2008): Cold tolerance of maize seedlings as determined by root morphology and photosynthetic traits. European Journal of Agronomy, 28(3), 178-185

ICF (2013) Greenhouse gas mitigation options and costs for agricultural land and animal production within the United States. Washington, DC. ICF International, Prepared for USDA, Climate Change Program Office

Iglesias A (2009) Policy issues related to climate change in Spain. In: Dinar A, Albiac A (Eds.) Policy and strategic behaviour in water resource management, Earthscan, London

Iglesias A, Cancelliere A, Cubillo F, Garrote L, Wilhite DA (2008a) Coping with drought risk in agriculture and water supply systems: Drought management and policy development in the Mediterranean. Springer, The Netherlands

Iglesias A, Garote L, Flores F, Moneo M (2007) Challenges to manage the risk of water scarcity and climate change in the Mediterranean. Water Resources Management, 21, 775-788

Iglesias A, Garrote L (2015) Adaptation strategies for agricultural water management under climate change in Europe. Agricultural Water Management, 155, 113-124

Iglesias A, Garrote L, Quiroga S, Moneo M (2012a) A regional comparison of the effects of climate change on agricultural crops in Europe. Climatic Change, 112(1), 29-46

Iglesias A, Garrote L, Quiroga S, Moneo M (2012b) From climate change impacts to the development of adaptation strategies: challenges for agriculture in Europe. Climatic Change, 112(1), 143-168

Iglesias A, Moneo M, Garrote L, Flores F (2008b) Drought and water scarcity: current and future vulnerability and risk. In: Garrido A, Llamas MR (Eds.) Issues in Water Resource Policy, Resources for the Future, Washington, DC

Iglesias A, Quiroga S, Diz A (2011a) Looking into the future of agriculture in a changing climate. European Review of Agricultural Economics, 38(3), 427-447

Iglesias A, Sánchez B, Garrote L, López I (2015) Towards adaptation to climate change: water for rice in the coastal wetlands of Doñana, Southern Spain. Water Resources Management, 1-25

Iglesias A, Schlickenrieder J, Pereira D, Diz A (2011b) From the farmer to global food production: use of crop models for climate change impact assessment. Handbook on Climate Change and Agriculture, pp. 49-72

Ingram J, Mills J, Frelih-Larsen A, Davis M, Merante P, Ringrose S, Molnar A, Sánchez B, Ghaley BB, Karaczun Z (2014) Managing soil organic carbon: a farm perspective. EuroChoices, 13(2), 12-19

Ingram J, Morris C (2007) The knowledge challenge within the transition towards sustainable soil management: an analysis of agricultural advisors in England. Land Use Policy, 24(1), 100-117

IPCC (2007a) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon SD, Qin MM, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 747–846

IPCC (2007b) Climate change 2007: synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Pachauri RK, Reisinger A (Eds.). Geneva, Switzerland, pp. 104

IPCC (2007c) Issues related to mitigation in the long term context. In: Climate change 2007: mitigation. Contribution of working group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 169–250

IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1535

IPCC (2014a) Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32

IPCC (2014b) Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1435

IPCC (2014c) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Pachauri RK, Meyer LA (Eds.) IPCC, Geneva, Switzerland, pp. 151

Isgin T, Bilgic A, Forster DL, Batte MT (2008) Using count data models to determine the factors affecting farmers' quantity decisions of precision farming technology adoption. Computers and Electronics in Agriculture, 62(2), 231-242

Johnson RJ, Doye D, Lalman DL, Peel DS, Curry Raper K, Chung C (2010) Factors affecting adoption of recommended management practices in stocker cattle production. Journal of Agricultural & Applied Economics, 42(1), 15-30

Jones L (2010) Overcoming social barriers to adaptation. ODI Background Note. London: ODI. www. odi.org.uk/resources/download/4945.pdf

Kahil MT, Albiac J (2013) Greenhouse gases mitigation policies in the agriculture of Aragon, Spain. Bio-based and Applied Economics, 2(1), 49-72

Kesicki F, Ekins P (2012) Marginal abatement cost curves: a call for caution. Climate Policy, 12(2), 219-236

Kesicki F, Strachan N (2011) Marginal abatement cost (MAC) curves: confronting theory and practice. Environmental Science & Policy, 14(8), 1195-1204

Kim SH, Dennis CG, Richard CS, Jeffrey TBD, Dennis JT, Vangimalla RR (2007) Temperature dependence of growth, development, and photosynthesis in maize under elevated CO_2. Environmental and Experimental Botany, 61(3), 224–236.

Kivlin JE, Filegel FC (1966) Attributes of Innovation as Factor in Diffusion. American Journal of Sociology, 72, 235-248

Klein RJT, Huq S, Denton F, Downing TE, Richels RG, Robinson JB, Toth FL (2007) Inter-relationships between adaptation and mitigation. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 745-777

Knowler D, Bradshaw B (2007) Farmers' adoption of conservation agriculture: a review and synthesis of recent research. Food Policy, 32(1), 25-48

Konidari P, Mavrakis D (2007) A multi-criteria evaluation method for climate change mitigation policy instruments. Energy Policy, 35(12), 6235-6257

Lal R (1999) Global carbon pools and fluxes and the impact of agricultural intensification and judicious land use. Prevention of land degradation, enhancement of carbon sequestration and conservation of biodiversity through land use change and sustainable land management with a focus on Latin America and the Caribbean. World Soil Resources Report 86. FAO, Rome, pp. 45-52

Lal R (2004) Carbon sequestration in dryland ecosystems. Environmental Management, 33(4), 528-544

Lal R (2013) Soil carbon management and climate change. Carbon Management, 4(4), 439-462

Lal R, Bruce JP (1999) The potential of world cropland soils to sequester C and mitigate the greenhouse effect. Environmental Science & Policy, 2(2), 177-185

Lal R, Kimble JM (1997) Conservation tillage for carbon sequestration. Nutrient Cycling in Agroecosystems, 49(1-3), 243-253

Lam SK, Chen D, Mosier AR, Roush R (2013) The potential for carbon sequestration in Australian agricultural soils is technically and economically limited. Nature. Scientific reports, 3

Lassaletta L, Aguilera E (2015) Soil carbon sequestration is a climate stabilization wedge: Comments on Sommer and Bossio (2014). Journal of Environmental Management, 153, 48-49

Lecina S, Isidoro D, Playán E, Aragüés R (2010). Irrigation modernization and water conservation in Spain: The case of Riegos del Alto Aragón. Agricultural Water Management, 97(10), 1663-1675

Lee JH (1979): Screening methods for cold tolerance at Crop Experiment Station Phytotron and at Chuncheon. In: Report of a rice cold tolerance workshop. International Rice Research Institute. Los Baños, Philippines, pp. 77-90

Leemans R, Kreileman GJJ, Berk M, Alcamo J, Swart R (1997) Scenarios, emission profiles, and safe emission corridors: applications of IMAGE 2. Global Enviromental Change, 35, 5-7

Lehenbauer PA (1914) Growth of maize seedlings in relation to temperature. Physiology Researches, 1, 247-288

Lesschen JP, van den Berg M, Westhoek HJ, Witzke HP, Oenema O (2011) Greenhouse gas emission profiles of European livestock sectors. Animal Feed Science and Technology, 166-167, 16-28

Livingston BE, Haasis FW (1933) Relations of time and maintained temperature to germination percentage for a lot of rice seed. American Journal of Botany, 20, 596-615

Lobell DB, Bänziger M, Magorokosho C, Vivek B (2011) Nonlinear heat effects on African maize as evidenced by historical yield trials. Nature Climate Change, 1(1), 42-45

Lobell DB, Field CB (2007) Global scale climate - crop yield relationships and the impacts of recent warming. Environmental Research Letters, 2(1), 14–21

Lobell DB, Sibley A, Ortiz-Monasterio JI (2012) Extreme heat effects on wheat senescence in India. Nature Climate Change, 2(3), 186–189

Long SP, Ainsworth EA, Rogers A, Ort DR (2004) Rising atmospheric carbon dioxide: plants FACE the future. Annual Review of Plant Biology, 55, 591-628

MacLeod M, Moran D, Eory V, Rees RM, Barnes A, Topp CFE, Ball B, Hoad S, Wall E, McVittie A, Pajot G, Matthews R, Smith P, Moxey A (2010) Developing greenhouse gas marginal abatement costs curves for agricultural emissions from crops and soils in the UK. Agricultural Systems, 103(4), 198–209

MAGRAMA (2011) Spanish Agricultural Census. Report on irrigation in Spain. Ministry of Agriculture, Food and Environment, Madrid, Spain

MAGRAMA (2012) Inventario de emisiones de gases de efecto invernadero de España e información adicional: 1990-2010 [Inventory of Spanish greenhouse gases emissions and additional information: 1990-2010]. Ministry of Agriculture, Food and Environment, Madrid, Spain

MAGRAMA (2013) Encuesta sobre Superficies y Rendimientos Cultivos. [Land use and Crop Yields Survey]. Ministry of Agriculture, Food and Environment, Madrid, Spain

Marquez-Garcia F, Gonzalez-Sanchez EJ, Castro-Garcia S, Ordóñez-Fernández R (2013) Improvement of soil carbon sink by cover crops in olive orchards under semiarid conditions. Influence of the type of soil and weed. Spanish Journal of Agricultural Research, 11(2), 335-346

Marsden T, Sonnino R (2008) Rural development and the regional state: Denying multifunctional agriculture in the UK. Journal of Rural Studies, 24(4), 422-431

Martín-López B, García-Llorente M, Palomo I, Montes C (2011) The conservation against development paradigm in protected areas: Valuation of ecosystem services in the Doñana social-ecological system (southwestern Spain).Ecological Economics, 70(8), 1481-1491

Matsui T, Omasa K, Horie T (2001) The difference in sterility due to high temperatures during the flowering period among japonica-rice varieties. Plant Production Science, 4(2), 90-93

McCown RL (2002) Locating agricultural decision support systems in the troubled past and socio-technical complexity of ‘models for management’. Agricultural systems, 74(1), 11-25

McKinsey & Company (2009) Pathways to a low-carbon economy – global greenhouse gases (GHG) abatement cost curve. Version 2 of the global greenhouse gas abatement cost curve – January 2009

Mendelsohn R, Dinar A, Williams L (2006) The distributional impact of climate change on rich and poor countries. Environment and Development Economics, 11(02), 159-178

Méndez PF, Isendahl N, Amezaga JM, Sanamaria L (2012) Facilitating transitional processes in rigid institutional regimes for water management and wetland conservation: experience from the Guadalquivir Estuary. Ecology and Society, 17(1), 26

Moran D, MacLeod M, Wall E, Eory V, McVittie A, Barnes A, Rees R, Topp C, Pajot G, Matthews R, Smith P, Moxey A (2011a) Developing carbon budgets for UK agriculture, land-use, land-use change and forestry out to 2022. Climatic change, 105(3-4), 529-553

Moran D, Macleod M, Wall E, Eory V, McVittie A, Barnes A, Rees R, Topp CFE, Moxey A (2011b) Marginal abatement cost curves for UK agricultural greenhouse gas emissions. Journal of Agricultural Economics, 62, 93-118

Morgan MI, Hine DW, Bhullar N, Loi NM (2015) Landholder adoption of low emission agricultural practices: A profiling approach. Journal of Environmental Psychology, 41, 35-44

Morris C, Potter C (1995) Recruiting the new conservationists: farmers' adoption of agri-environmental schemes in the UK. Journal of rural studies, 11(1), 51–63

Moser SC, Elkstrom JA (2011) Taking ownership of climate change: participatory adaptation planning in two local case studies from California. J Environ Stud Sci 1, 63–74

Moss RH, Edmonds J, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. Nature, 463(7282), 747-756

Muchow RC (1990) Effect of high temperature on grain-growth in field-grown maize. Field Crops Research, 23(2), 145-158

Mustajoki J, Hämäläinen RP (2000) Web-HIPRE: global decision support by value tree and AHP analysis. INFOR J, 38(3), 208-220

Mustajoki J, Hämäläinen RP, Marttunen M (2004) Participatory multicriteria decision analysis with WebHIPRE: a case of lake regulation policy. Environmental Modelling & Software, 19(6), 537–547

Nakicenovic N, Alcamo J, Grubler A, Riahi K, Roehrl RA, Rogner H-H, Victor N et al. (2000) Special Report on Emissions Scenarios (SRES), A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK

Nieto OM, Castro J, Fernandez-Ondono E (2013) Conventional tillage versus cover crops in relation to carbon fixation in Mediterranean olive cultivation. Plant and Soil 365(1-2), 321-335

Ninyerola M., Pons X, Roure JM (2005) Atlas climático digital de la península ibérica. Metodología y aplicaciones en bioclimatología y geobotánica. Universidad Autónoma de Barcelona, Bellaterra

Nishiyama I (1976) Effects of temperature on the vegetative growth of rice plants. In: Enviromental control of growth and yield. Proceedings of the Symposium on Rice and Climate. International Rice Research Institute. Los Baños, Philippines, pp. 159-185

Norris PE, Batie SS (1987) Virginia farmers' soil conservation decisions: an application of Tobit analysis. Southern Journal of Agricultural Economics, 19(1), 79-89

O'Brien D, Shalloo L, Crosson P, Donnellan T, Farrelly N, Finnan J, Hanrahan K, Lalor S, Lanigan G, Thorne F, Schulte R (2014) An evaluation of the effect of greenhouse gas accounting methods on a marginal abatement cost curve for Irish agricultural greenhouse gas emissions. Environmental Science & Policy, 39, 107-118

O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR, Mathur R, van Vuuren DP (2014) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change, 122(3), 387-400

Oda Y, Honda T (1963) Environmental control of tillering in rice plants. Reports of the Institute for Agricultural Research Tohoku University, 14, 15-36

OECD (2012a) Looking to 2060: Long-term global growth prospects - OECD. Paris, France

OECD (2012b) Farmer Behaviour, Agricultural Management and Climate Change, OECD Publishing. http://dx.doi.org/10.1787/9789264167650-en

Ogle SM, Breidt FJ, Paustian K (2005) Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry, 72(1), 87-121

Ojeda J, Álvarez JI, Martín D, Fraile P (2009) El uso de las TIG para el cálculo del índice de vulnerabilidad costera (CVI) ante una potencial subida del nivel del mar en la costa andaluza (España). GeoFocus, 9, 83-100

Olesen JE, Bindi M (2002) Consequences of climate change for European agricultural productivity, land use and policy. European journal of agronomy, 16(4), 239-262

Olesen JE, Trnka M, Kersebaum K, Skjelvåg A, Seguin B, Peltonen-Sainio P, Rossi F, Kozyra J, Micale F (2011) Impacts and adaptation of European crop production systems to climate change. European Journal of Agronomy, 34(2), 96-112

Olsen JK, McMahon CR, Hammer GL (1993) Prediction of sweet corn phenology in subtropical environment. Agronomy Journal, 85(2), 410-415

Owen PC (1971) The effects of temperature on the growth and development of rice. Field Crop Abstracts, 24(1), 1-8

Pacala S, Socolow R (2004) Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. Science, 305(5686), 968-972

Palmer MA, Reidy Liermann CA, Nilsson C, Flörke M, Alcamo J, LakePS, Bond N (2008) Climate change and the world's river basins: anticipating management options. Frontiers in Ecology and the Environment, 6(2), 81-89

Palomo I, Martín-López B, López-Santiago C, Montes C (2011) Participatory scenario planning for protected areas management under the ecosystem services framework: the Doñana social-ecological system in southwestern Spain. Ecology and Society, 16(1), 23

Parent B, Tardieu F (2012) Temperature responses of developmental processes have not been affected by breeding in different ecological areas for 17 crop species. New Phytologist, 194(3), 760-774

Parent B, Turc O, Gibon Y, Stitt M, Tardieu F (2010) Modelling temperature-compensated physiological rates, based on the co-ordination of responses to temperature of developmental processes. Journal of Experimental Botany, 61(8), 2057–2069

Park SJ, Hwang CS, Vlek PLG (2005) Comparison of adaptive techniques to predict crop yield response under varying soil and land management conditions. Agricultural Systems, 85(1), 59-81

Parry ML, Rosenzweig C, Iglesias A, Livermore M, Fischer G (2004) Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environmental Change, 14(1), 53-67

Paustian K, Collins HP, Paul EA (1997) Management controls on soil carbon P. In: Paul EA, Paustian K, Elliott ET, Cole CV (eds) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, Florida, pp. 15-49

Pellerin S, Bamière L, Angers D, Béline F, Benoît M, Butault JP, Chenu C, Colnenne-David C, De Cara S, Delame N, Doreau M, Dupraz P, Faverdin P, Garcia-Launay F, Hassouna M, Hénault C, Jeuffroy MH, Klumpp K, Metay A, Moran D, Recous S, Samson E, Savini I & Pardon L (2013) How can French agriculture contribute to reducing greenhouse gas emissions? Abatement potential and cost of ten technical measures, Summary of the study report, INRA (France), pp. 92

Picketts IM, Curry J, Déry SJ, Cohen SJ (2013) Learning with practitioners: climate change adaptation priorities in a Canadian community. Climatic change, 118(2), 321-337

Poe GL, Bills NL, Bellows BC, Crosscombe P, Koelsch RK, Kreher MJ, Wright P (2001) Will voluntary and educational programs meet environmental objectives: evidence from a survey of New York dairy farms. Review of Agricultural Economics, 23(2): 473-491

Porter JR, Gawith M (1999) Temperatures and the growth and development of wheat: a review. European Journal of Agronomy, 10(1), 23-36

Porter JR, Semenov MA (2005) Crop responses to climatic variation. Philosophical Transactions of the royal Society Interface B-Biological Science, 360(1463), 2021-2035

Powlson DS, Stirling CM, Jat ML, Gerard BG, Palm CA, Sanchez PA, Cassman KG (2014) Limited potential of no-till agriculture for climate change mitigation. Nature Climate Change, 4(8), 678-683

Prager K, Posthumus H (2010) Socio-economic factors influencing farmers’ adoption of soil conservation practices in Europe. In: Napier TL (ed) Human dimensions of soil and water conservation. Nova Science Publishers Inc, New York, pp. 203-223

Prasad PVV, Boote K.J, Allen LH Jr, Sheehy JE, Thomas JMG (2006) Species, ecotype and cultivar differences in spikelet fertility and harvest index of rice in response to high temperature stress. Field Crops Research, 95(2), 398-411

Prokopy L, Floress SK, Klotthor-Weinkauf D, Baumgart-Getz A (2008) Determinants of agricultural best management practice adoption: evidence from the literature. Journal of Soil and Water Conservation, 63(5), 300-311

Pulido-Calvo I, Gutiérrez-Estrada JC, Savic D (2012) Heuristic modelling of the water resources management in the Guadalquivir River Basin, Southern Spain. Water Resources Management, 26(1), 185-209

Puteh AB, Roziah R, Mohamad RB (2010) Dormancy and cardinal temperatures during seed germination of five weedy rice (Oryza spp.) strains. Journal of Tropical Agricultural Science, 33(2), 243-250

Quevauviller P, Balabanis P, Fragakis C, Weydert M, Oliver M, Kaschl A, Arnold G, Kroll A, Galbiati L, Zaldivar JM, Bidoglio G (2005) Science-policy integration needs in support of the implementation of the EU Water Framework Directive. Environmental Science & Policy, 8(3), 203-211

Rahelizatovo NC, Gillespie JM (2004) The adoption of best-management practices by Louisiana dairy producers. Journal of Agricultural and Applied Economics, 36(1), 229-240

Ramieri E, Hartley A, Barbanti A, Duarte Santos F, Gomes A, Hilden M, Laihonen P, Marinova N, Santini M (2011) Methods for assessing coastal vulnerability to climate change. European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation (ETC CCA) Technical Paper, Bologna (IT), pp. 93

Ramos ME, Benítez E, García PA, Robles AB (2010) Cover crops under different managements vs. frequent tillage in almond orchards in semiarid conditions: effects on soil quality. Applied Soil Ecology, 44(1), 6-14

Rauschmayer F, Wittmer H (2006) Evaluating deliberative and analytical methods for the resolution of environmental conflicts. Land Use Policy, 23(1), 108-122

Reed MS, Fraser ED, Dougill AJ (2006) An adaptive learning process for developing and applying sustainability indicators with local communities. Ecological Economics, 59(4), 406-418

Rehl T, Müller J (2013) CO_2 abatement costs of greenhouse gas (GHG) mitigation by different biogas conversion pathways. Journal of Environmental Management, 114, 13-25

Reidsma P, Ewert F, Lansink AO, Leemans R (2010) Adaptation to climate change and climate variability in European agriculture: the importance of farm level responses. European Journal of Agronomy, 32(1), 91-102

Rey D, Garrido A, Calatrava J (2014). The Water Markets in Spain: moving towards 21st century mechanisms and approaches with 20th century regulations. In: Water Markets for the 21st. Century: What Have We Learned?. Easter W, Huang Q (Eds.). Springer, pp. 127-147

Rijsberman FR (2006) Water scarcity: fact or fiction?. Agricultural Water Management, 80(1), 5-22

Robert PC (2002) Precision agriculture: a challenge for crop nutrition management. Plant and Soil, 247(1), 143-149

Rosenzweig C, Iglesias A (1994) Implications of climate change for international agriculture: crop modeling study. EPA 230-B-94-003. U.S. EPA Office of Policy, Planning and Evaluation, Climate Change Division, Adaptation Branch, Washington, DC

Rosenzweig C, Parry ML (1994) Potential impact of climate change on world food supply. Nature, 367(6459), 133-138

Ross H, Shaw S, Rissik D, Cliffe N, Chapman S, Hounsell V, Udy J, Trinh NT, Schoeman J (2015) A participatory systems approach to understanding climate adaptation needs. Climatic Change, 1-16

Rötter RP, Carter TR, Olesen JE, Porter JR (2011) Crop-climate models need an overhaul. Nature Climate Change, 1(4), 175–177

Sánchez B, Álvaro-Fuentes J, Cunningham R, Iglesias A (2014a) Towards mitigation of greenhouse gases by small changes in farming practices: understanding local barriers in Spain. Mitigation and Adaptation Strategies for Global Change, 1-34

Sánchez B, Rasmussen A, Porter JR (2014b) Temperatures and the growth and development of maize and rice: a review. Global Change Biology, 20(2), 408-417

Sandelowski M (1995) Sample size in qualitative research. Research in nursing & health, 18(2), 179-183

Sanz-Cobena A, García-Marco S, Quemada M, Gabriel JL, Almendros P, Vallejo A (2014) Do cover crops enhance N_2O, CO_2 or CH_4 emissions from soil in Mediterranean arable systems? Science of the Total Environment, 466, 164-174

Satake T, Yoshida S (1978) High temperature-induced sterility in indica rice at flowering. Japanese Journal of Crop Science, 47, 6-17

Schellnhuber HJ, Hare W, Serdeczny O, Hare W, Serdeczny O, Adams S, Coumou D, Frieler K, Martin M, Otto IM, Perrette M, Robinson A, Rocha M, Schaeffer M, Schewe J, Wang X, Warszawski L (2012) Turn Down the Heat: Why a 4°C Warmer World Must be Avoided. World Bank, Washington, DC, pp. 1–106

Schoper JB, Lambert RJ, Vasilas BL (1987) Pollen variability, pollen shedding, and combining ability for tassel heat tolerance in maize. Crop Science, 27(1), 27-37

Sharma D, Das Gupta A, Babel MS (2007) Spatial disaggregation of bias-corrected GCM precipitation for improved hydrological simulation: Ping river basin, Thailand. Hydrology and Earth Systems Sciences, 11(4), 1373-1390

Shaykewich CF (1994) An appraisal of cereal crop phenology modelling. Canadian Journal of Plant Science, 75(2), 329-341

Sinsawat V, Leipner J, Stamp P, Fracheboud Y (2004) Effect of heat stress on the photosynthetic apparatus in maize (Zea mays L.) grown at control or high temperature. Environmental and Experimental Botany, 52(2), 123-129

Smith P (2004) Carbon sequestration in croplands: the potential in Europe and the global context. European journal of agronomy, 20(3), 229-236

Smith P (2012) Soils and climate change. Current Opinion in Environmental Sustainability, 4, 539-544

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O (2007b) Agriculture. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (Eds.) Climate Change 2007: mitigation. Contribution of Working

Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 497–540

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O’Mara F, Rice C (2007a) Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agriculture, Ecosystems & Environment, 118(1), 6–28

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O, Howden M, McAllister T, Pan G, Romanenkov V, Dchneider U, Towprayoon S, Wattenbach M, Smith J (2008) Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1492), 789-813

Smith P, Olesen JE (2010) Synergies between mitigation of, and adaptation to, climate change in agriculture. The Journal of Agricultural Science, 148(05), 543-552

Smith P, Powlson DS, Glendinning MJ, Smith JU (1997) Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. Global Change Biology, 3(1), 67-79

Snyder CS, Bruulsema TW, Jensen TL, Fixen PE (2009) Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agriculture, Ecosystems & Environment, 133(3), 247-266

Soane BD, Ball BC, Arvidsson J, Basch G, Moreno F, Roger-Strade J (2012) No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil and Tillage Research, 118, 66-87

Sommer R, Bossio D (2014) Dynamics and climate change mitigation potential of soil organic carbon sequestration. Journal of Environmental Management, 144, 83-87

Stainforth DA, Aina T, Christensen C, Collins M, Faull N, Frame DJ, Kettleborough JA, Knight S, Martin A, Murphy JM, Piani C, Sexton D, Smith LA, Spicer RA, Thorpe AJ, Allen MR (2005) Uncertainty in predictions of the climate response to rising levels of greenhouse gases. Nature, 433(7024), 403-406

Steenwerth K, Belina KM (2008) Cover crops enhance soil organic matter, carbon dynamics and microbial function in a vineyard agroecosystem. Applied Soil Ecology, 40(2): 359-369

Stern N (2007) The Economics of Climate Change: the Stern Review. Cambridge University Press, Cambridge

Stone P (2001) The effects of heat stress on cereal yield and quality. In Crop Responses and Adaptations to Temperature Stress (Eds. Basra AS). Food Products Press, Binghamton, NY, USA, pp. 243–291

Sunding D, Zilberman D (2001) The agricultural innovation process: research and technology adoption in a changing agricultural sector. In: Gardner BL, Rausser GC (Eds.) Agricultural Production, Handbook of Agricultural Economics, vol. 1, Elsevier, New York, pp. 207-261

Tambo JA, Abdoulaye T (2012) Climate change and agricultural technology adoption: the case of drought tolerant maize in rural Nigeria. Mitigation and Adaptation Strategies for Global Change, 17(3), 277-292

Tao F, Yokozawa M, Zhang Z (2009) Modelling the impacts of weather and climate variability on crop productivity over a large area: a new process-based model development, optimization, and uncertainties analysis. Agricultural and Forest Meteorology, 149(5), 831-850

Tisdell J (2010) Acquiring water for environmental use in Australia: an analysis of policy options. Water Resources Management, 24(8), 1515-1530

Tol RS (2009) The economic effects of climate change. The Journal of Economic Perspectives, 29-51

Tollenaar M, Bruulsema TW (1988) Efficiency of maize dry matter production during periods of complete leaf area expansion. Agronomy Journal, 80(4), 580–585

Tollenar M, Danard TB, Hunter RB (1979) Effect of temperature on rate of leaf appearance and flowering date in maize. Crop Science, 19(3), 363-370

Trnka M, Eitzinger J, Semerádová D, Hlavinka P, Balek J, Dubrovský M, Žalud Z (2011) Expected changes in agroclimatic conditions in Central Europe. Climatic change, 108(1-2), 261-289

Ueki K (1960) The influence of temperature of irrigation water upon the growth of paddy rice in the warmer district. The injuries due to high water temperature on development of young panicle. Proceedings of the Crop Science Society of Japan, 29, 75-78

UNFCCC (2008) Challenges and opportunities for mitigation in the agricultural sector: technical paper. United Nation Framework Convention on Climate Change. Available at: http://unfccc.int/resource/docs/2008/tp/08.pdf

UNFCCC (2011) Assessing the costs and benefits of adaptation options. The Nairobi Work Programme on impacts, vulnerability and adaptation to climate change. United Nations Framework Convention on Climate Change. http://unfccc.int/resource/docs/publications/pub_nwp_costs_benefits_adaptation.pdf

van Aalst MK, Cannon T, Burton I (2008) Community level adaptation to climate change: the potential role of participatory community risk assessment. Global Environmental Change, 18(1),165-179

van Doorslaer B, Witzke P, Huck I, Weiss F, Fellmann T, Salputra G, Jansson T, Drabik D, Leip A (2015). An economic assessment of GHG mitigation policy options for EU agriculture. JRC Technical Reports, European Commission, Seville. https://ec.europa.eu/jrc/sites/default/files/jrc90788_ecampa_final.pdf

van Vuuren DP, Carter TR (2013) Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old. Climatic Change, Special Issue, Nakicenovic N, Lempert R, Janetos A (Eds.) A Framework for the Development of New Socioeconomic Scenarios for Climate Change Research

van Vuuren DP, Edmonds J, Kainuma MLT, Riahi K, Thomson A, Matsui T, Hurtt G, Lamarque JF, Meinshausen M, Smith S, Grainer C, Rose S, Hibbard KA, Nakicenovic N, Krey V, Kram T (2011a) Representative concentration pathways: An overview. Climatic Change, 109, 5-31

van Vuuren DP, Isaac M, Kundzewicz ZW, Arnell N, Barker T, Criqui P, Berkhout F, Hilderink H, Hinkel J, Hof A, Kitous A, Kram T, Mechler R, Scrieciu S (2011b) The use of scenarios as the basis for combined assessment of climate change mitigation and adaptation. Global Environmental Change, 21(2), 575-591

van Vuuren DP, Kriegler E, O'Neill BC, Ebi KL, Riahi K, Carter TR, Edmonds J, Hallegatte S, Kram T, Mathur R, Winkler H (2013) A new scenario framework for Climate Change Research: scenario matrix architecture. Climatic Change, Special Issue, Nakicenovic N, Lempert R, Janetos A (Eds.) A Framework for the Development of New Socioeconomic Scenarios for Climate Change Research

Varela-Ortega C, Blanco-Gutiérrez I, Esteve P, Bharwani S, Fronzek S, Downing TE (2013) How can irrigated agriculture adapt to climate change? Insights from the Guadiana Basin in Spain. Regional Environmental Change, 1-12

Varis O, Kajander T, Lemmela R (2004) Climate and water: from climate models to water resources management and vice versa. Climatic Change, 66(3), 321-344

Velthof GL, Oudendag D, Witzke HP, Asman WAH, Klimont Z, Oenema O (2009) Integrated assessment of nitrogen emissions from agriculture in EU-27 using MITERRA-EUROPE. Journal of Environmental Quality, 38, 402-417

Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TJ, Fromentin JM, Hoegh-Guldberg O, Bairlein F (2002). Ecological responses to recent climate change. Nature, 416(6879), 389-395

Wang W, Koslowski F, Nayak DR, Smith P, Saetnan E, Ju X, Guo L, Han G, de Perthuis C, Lin E & Moran D (2014) Greenhouse gas mitigation in Chinese agriculture: Distinguishing technical and economic potentials. Global Environmental Change, 26, 53-62

Ward CE, Vestal MK, Doye DG, Lalman DL (2008) Factors affecting adoption of cow-calf production practices in Oklahoma. Journal of Agricultural and Applied Economics, 40(3), 851-863

Ward DJ (2014) The failure of marginal abatement cost curves in optimising a transition to a low carbon energy supply. Energy Policy, 73, 820-822

Warrington IJ, Kanemasu ET (1983) Corn growth response to temperature and photoperiod I. Seedling emergence, tassel initiation and anthesis. Agronomy Journal, 75(5), 749-754

Wei Y, Langford J, Willett IR, Barlow S, Lyle C (2011) Is irrigated agriculture in the Murray Darling Basin well prepared to deal with reductions in water availability?. Global Environmental Change, 21(3), 906-916

West TO, Post WM (2002) Soil organic carbon sequestration rates by tillage and crop rotations: A global data analysis. Soil Science Society of America Journal, 66(6), 1930-1946

Wheeler TR, Hong TD, Ellis RH, Batts GR, Morison JIL, Hadley P (1996a) The duration and rate of grain growth, and harvest index,of wheat (Triticum aestivum) in response to temperature and CO_2. Journal of Experimental Botany, 47(5), 623–630

Wheeler TR, Batts GR, Ellis RH, Hadley P, Morison JIL (1996b) Growth and yield of winter wheat (Triticum aestivum) crops in response to CO_2 and temperature. Journal of Agricultural Science, 127(1), 37-48

Wheeler TR, Craufurd PQ, Ellis RH, Porter JR, Prasad PVV (2000) Temperature variability and the yield of annual crops. Agriculture, Ecosystems & Environment, 82(1), 159-167

Whyte WF (1991) Participatory action research. Sage, Newbury Park, CA, pp. 247

Willaarts BA, Ballesteros M, Hernández-Mora N (2014) Ten years of the Water Framework Directive in Spain: An overview of the ecological and chemical status of surface water bodies. In: Martínez-Santos P, Aldaya MM and Llamas MR (Eds.) Integrated Water Resources Management in the 21st Century: Revisiting the paradigm. Taylor and Francis, Leiden, pp. 99-120

Yagüe MR, Quílez D (2010) Cumulative and residual effects of swine slurry and mineral nitrogen in irrigated maize. Agronomy Journal, 102(6), 1682-1691

Yamakawa Y, Kishikawa H (1957) On the effect of temperature upon the division and elongation of cells in the root of rice plant. Proceedings of the Crop Science Society of Japan, 26, 94-95

Yin X, Kropff L, Martin J, McLaren G, Visperas RM (1995) A nonlinear model for crop development as a function of temperature. Agricultural and Forest Meteorology, 77(1), 1-16

Yin XY, Kropff MJ (1996) The Effect of Temperature on Leaf Appearance in Rice. Annals of Botany, 77(3), 215-221

Yoshida S (1981) Fundamentals of rice crop science. Laguna International Rice Research Institute. Los Banos, Philippines, pp. 269

Annexes

Annex 1. Complete dataset and references for the meta-analysis

Complete dataset

Table A1.1. Lethal temperature limits for rice

Literature source	Tmin (ºC)	Tmax (ºC)	Specie	Sub-specie	Cultivar	Conditions
Baker 2004		40	Oryza Sativa L.	Japonica	Cocodrie, Cypress, Jefferson	Rice growing regions of Texas and Louisiana
Lee 1979	10		Oryza Sativa L.	Hybrid	Tongil, Yushin, Suweon 258, Suweon 264, Suweon 264, Suweon 278 Milyang 29, Milyang 30	Seedling death
Yoshida 1981	8	40	Oryza Sativa L.	Not specified		Seedling death
Yoshida 1981		45	Oryza Sativa L.	Not specified		No germination
Chaudhary et al. 1969	4.5	43	Oryza Sativa L.	Not specified	Not specified	No germination
Livingston et al. 1933		45	Oryza Sativa L.	Not specified	Not specified	No germination
Puteh et al. 2010	0.4	43	Oryza Sativa L.	Japonica	MR73	No germination
Hamdani 1979	7		Oryza Sativa L.	Not specified	Not specified	Seedling death
Nishiyama 1976	0		Oryza Sativa L.	Not specified		No germination
Nishiyama 1976	2-5		Oryza Sativa L.	Not specified		Seedling death
Yamakawa et al.1957		43	Oryza Sativa L.	Not specified		No elongation of the seminal root
Ehrler et al. 1958		42	Oryza Sativa L.	Hybrid	Caloro	No root growth
Fadzillah et al.1996	4		Oryza Sativa L.	Japonica	Taipei 309	No shoot growth
Han et al. 2009		45	Oryza Sativa L.	Japonica	Not specified	No leaf development

Table A1.2. Base (Tmin), optimum (Topt) and maximum (Tmax) cardinal temperatures for different key growth processes in rice

Literature source	Tmin (ºC)	Topt (ºC)	Tmax (ºC)	Specie	Sub-specie	Cultivar	Conditions
Leaf initiation							
Yin & Kropff 1996a		32		Oryza Sativa L.	Indica	IR36,IR42, IR64,IR72, Azucena, MR84	Controlled chamber at five diurnally constant temperature 22,24,26,28,32
Yin & Kropff 1996a				Oryza Sativa L.	Indica	Shan You63, IR64616H	
Yin & Kropff 1996a				Oryza Sativa L.	Japonica	Nipponbare, Koshihikari, Hwasong	
Yoshida 1981	7-12	31	45	Oryza Sativa L.	Not specified	Not specified	
Ellis et al. 1993	11.6	26		Oryza Sativa L.	Indica	IR36	Cabinets in free-draining or water logged pots at 20,24 or 28ºC
Kiniry et al. 1991	7-9			Oryza Sativa L.	Not specified	Not specified	
Mitchell et al. 2000		25-30		Oryza Sativa L.	Indica	IR72	
Murakami 1987	11			Oryza Sativa L.	Japonica	Kitakogane, kitahikari, Matsumae	
Gao et al. 1992	10	28		Oryza Sativa L.	Japonica	Not specified	
Gao et al. 1992	12	30		Oryza Sativa L.	Indica	Not specified	
Gao et al. 1992	13			Oryza Sativa L.	Hybrid	Not specified	
Baker et al. 1992		34	40	Oryza Sativa L.	Indica	IR36	Chambers at CO2([330];[660]
Sié et al. 1998		26-30		Oryza Sativa L.	Indica	Jaya,IRG4	Experiments at Sahel Station, Senegal
Sié et al. 1998				Oryza Sativa L.	Japonica	IKP	
Manalo et al. 1994				Oryza Sativa L.	Indica	IR28, IR36,IR64	
Manalo et al. 1994		29		Oryza Sativa L.	Japonica	ITA 186, Morobereka, Salumpik	Temperature and humidity controlled growth chambers
Shoot growth							
Dingkuhn et al. 1995	9-14	23-31		Oryza Sativa L.	Indica	IR64,IR3941 ,Jaya,BG90, KH998, SIPI6920	Different photothernal environments at two sites in Senegal
Dingkuhn et al. 1995				Oryza Sativa L.	Japonica	IKP	

Literature source	Tmin (ºC)	Topt (ºC)	Tmax (ºC)	Specie	Sub-specie	Cultivar	Conditions
Yoshida 1981	10			Oryza Sativa L.	Not specified	Not specified	
Chaudhary et al. 1970a	15-20	25-30	35	Oryza Sativa L.	Indica	Taichung1	Controlled chamber at constant temperatures (10,15,20,25,30 ,40ºC) & 8 hours day light
Chaudhary et al. 1970b		20-32	30-42	Oryza Sativa L.	Indica	Taichung1	Controlled temperature water baths at cyclic costant soil temperature 22/10,27/15,32/ 20,37/25,42/30
Herath et al.1965	16 (Tw)	32 (Tw)		Oryza Sativa L.	Hybrid	Caloro, Colusa, Calrose, Bluebonne, Gulfrose, Patna	Controlled environment in a greenhouse at constant temperatures (16,24,27,32ºC)
Khan et al. 1987		30		Oryza Sativa L.	Indica	IR28	Controlled environment at different temperatures (30,25/30,35)
Root growth							
Yoshida 1981	16	25-28	35	Oryza Sativa L.	Not specified	Not specified	
Matsushima et al. 1968	16(Tw)	21	36	Oryza Sativa L.	Not specified	Not specified	
Matsushima et al. 1968		31		Oryza Sativa L.	Not specified	Not specified	
Chaudhary et al. 1970a	15-20	25-30	35	Oryza Sativa L.	Indica	Taichung1	Controlled chamber at constant temperatures (10,15,20,25,30 ,40ºC) and 8 hours day light
Chaudhary et al. 1970b		20-32	30-42	Oryza Sativa L.	Indica	Taichung1	Controlled temperature water baths at constant soil temperature (22/10,27/15,32 /20,37/25,42/30
Hamdani 1979	15	28-31		Oryza Sativa L.	Not specified	Not specified	Hill conditions in India
Ehrler et al. 1958		30	37	Oryza Sativa L.	Hybrid	Caloro	Controlled environment in a greenhouse at constant temperatures (18,30,37ºC)

Literature source	Tmin (ºC)	Topt (ºC)	Tmax (ºC)	Specie	Sub-specie	Cultivar	Conditions
Ueki 1960	12 (Tw)	26 (Tw)	32(Tw)	Oryza Sativa L.	Japonica	Norin 37	Treatment at constant water temp (26,32,37) in greenhouse and open air
Ueki 1960	19 (Tw)			Oryza Sativa L.	Japonica	Norin 18	Treatment at constant water temp (26,32,37) in greenhouse and open air
Herath et al. 1965		32 (Tw)		Oryza Sativa L.	Hybrid	Caloro, Colusa, Calrose, Bluebonne, Gulfrose, Patna	Controlled environment in a greenhouse at constant temperatures (16,24,27,32ºC)
Herath et al. 1965		24 (Tw)		Oryza Sativa L.	Hybrid	Caloro, Colusa, Calrose, Bluebonne, Gulfrose, Patna	Controlled environment in a greenhouse at constant temperatures (16,24,27,32ºC)
Yamakawa et al.1957	15	30	40	Oryza Sativa L.	Not specified	Not specified	

Table A1.3. Base (Tmin), optimum (Topt) and maximum (Tmax) cardinal temperatures for key phenological phases and development stages in rice

Literature source	Tmin (ºC)	Topt (ºC)	Tmax (ºC)	Specie	Sub-specie	Cultivar	Conditions
Germination/Emergence							
Puteh et al. 2010	10	24.3	35	Oryza Sativa L.	Japonica	MR73	
Yoshida 1981	10	20-35	40	Oryza Sativa L.	Not specified	Not specified	
Livingston et al. 1933	12	37	42	Oryza Sativa L.	Not specified	Standard cultures	Chambers at 8-55ºC
Shibata 1979	12-15			Oryza Sativa L.	Not specified	Not specified	Hokkaido district
Lee 1979	10	19		Oryza Sativa L.	Hybrid	Tongil, Suweon214, Suweon215	Phytotron test at 10,13,16,19,22ºC
Lee 1979					Japonica	Paldal, Suweon82, Pungkwang, Jinheung, Palgeum, Akibar, Senshuraku, Shirogane, Fujisaka5, Norin 6	
Oka 1954	11			Oryza Sativa L.	Japonica	Not specified	Germination test at 6 different temperatures 11,7 to 30ºC
Oka 1954	17						
Owen 1971			40-45	Oryza Sativa L.	Not specified	Not specified	
Nishiyama 1976		15-35		Oryza Sativa L.	Hybrid	T136	
Nishiyama 1976					Indica	Kaluheenati, IR8	
Chaudhary et al. 1969	7	32-37.5	41	Oryza Sativa L.	Indica	Dular	Chambers(4,5,10,15,5 ,21,26,5,32,37,5,45ºC) &day light periods(8,12,16h,)
Tillering							
Yoshida 1981	9-16	25-31	33	Oryza Sativa L.	Not specified	Not specified	
Matsushima et al. 1968	16	31	36	Oryza Sativa L.	Not specified	Not specified	
Oda et al. 1963	19	23	32	Oryza Sativa L.	Japonica	Rikuu 20, Ohu 204	Natural conditions in Tohoku
Oda et al. 1963				Oryza Sativa L.	Japonica	Norin17	
Sato 1972	15	25	35	Oryza Sativa L.	Indica	IR8	Chamber at day(12 hr)/night (12hr) temp,(35-30,30-25,25-20,20-15,15-10)under natural light
Lee 1979	15			Oryza Sativa L.	Hybrid	Tongil	Test in phytotron at Suweon

Literature source	Tmin (ºC)	Topt (ºC)	Tmax (ºC)	Specie	Sub-specie	Cultivar	Conditions
Lee 1979	20			Oryza Sativa L.	Japonica	Jinheung	Test in phytotron at Suweon
Baker et al. 1992		28-34	40	Oryza Sativa L.	Indica	IR36	Controlled chambers at ([330];[660]CO2)
Hamdani 1979	18	28		Oryza Sativa L.	Not specified	Not specified	Hill conditions in India
Hoshino et al. 1969	16	31	36	Oryza Sativa L.	Not specified	Not specified	Controlled air and water temp(16,21,31,36ºC)
Ueki 1966		20-26		Oryza Sativa L.	Not specified	Not specified	
Manalo et al. 1994		33		Oryza Sativa L.	Indica	IR28, IR36,IR64	
Manalo et al. 1994				Oryza Sativa L.	Japonica	ITA 186, Moroberekan, Salumpikit	Temp & %HR controlled growth chambers
Matsushima et al. 1964	16(Tw)	31(Tw)		Oryza Sativa L.	Japonica	Norin25	Air-temp/water temp(36,31,21,16)
Panicle Initiation							
Yoshida 1981	15			Oryza Sativa L.	Not specified	Not specified	
Adachi 1972	15	20-25	30	Oryza Sativa L.	Japonica	Norin11, Norin15	Tº(15,20,25,30ºC)&8/16 h, photoperiod
Dingkuhn et al. 1995	11.4			Oryza Sativa L.	Indica	IR64,IR3941,Jaya,BG90,KH 998, SIPI6920	Photothernal environments in Senegal
Dingkuhn et al. 1995				Oryza Sativa L.	Japonica	IKP	
Roberts et al. 1965			33.3	Oryza Sativa L.	Indica	Lead35,Radin China4,Gantang,Mas2401, Joboi22I, Heenati	Environments(35-25,35-30,40-30,35-35ºC)
Roberts et al. 1965				Oryza Sativa L.	Japonica	Taichu65,PeBi Un	
Roberts et al. 1965				Oryza Glaberrima S	Japonica	Kogbati3, Legbeh	
Lee 1979	17			Oryza Sativa L.	Japonica	Jinheung	
Lee 1979				Oryza Sativa L.	Hybrid	Tongil,Yushin suweon264, Milyang29	Test in phytotron at Suweon
Shimizu et al. 1966	14-18			Oryza Sativa L.	Not specified	Not specified	
Matsushima et al. 1964	16	31	36	Oryza Sativa L.	Japonica	Norin25	Air-temp/water temp(36,31,21,16)
Anthesis							
Yoshida 1981	22	30-33	35	Oryza Sativa L.	Not specified	Not specified	
Jagadish et al.2007			33.7	Oryza Sativa L.	Indica	IR64	30/24ºC day-night temp in greenhouse
Jagadish et al. 2007				Oryza Sativa L.	Japonica	Azucena	

Literature source	Tmin (ºC)	Topt (ºC)	Tmax (ºC)	Specie	Sub-specie	Cultivar	Conditions
Satake et al. 1978		29	36.5	Oryza Sativa L.	Indica	N22	Treatment (8 hrs, high temp, a day/ 21ºC at night) in naturaly lighted rooms of phytotron
Satake et al. 1978			35	Oryza Sativa L.	Indica	IR747	
Satake et al. 1978			32.2	Oryza Sativa L.	Hybrid	BKN6624	
Satake et al. 1978			41	Oryza Sativa L.	Indica/hybrid	N22, IR747, BKN6624	
Vergara et al. 1970	22	30		Oryza Sativa L.	Indica	IR8	Growth Chambers
Satake et al. 1970	12	24		Oryza Sativa L.	Japonica	Hayayuki	Phytotron natural light rooms
Satake et al. 1970		26		Oryza Sativa L.	Japonica	Norin20	
Yin et al. 1996b		26		Oryza Sativa L.	Indica	IR8,IR36,IR42,IR64,IR72, CO36,MR84, ADT36,TN1, Shan, You63, IR64616H	Naturaly lighted chambers
Yin et al. 1996b				Oryza Sativa L.	Japonica	Nipponbare koshihikari, Eiko, Fujisaka, Xiu Sgui, Stejaree, Hwasong	
Shahi et al. 1979	18			Oryza Sativa L.	Not specified	Not specified	Experiments in Khumaltar
Shahi et al. 1979	15			Oryza Sativa L.	Not specified	Not specified	Experiments in Jumla Valley
Shibata 1979	12-16	20-25		Oryza Sativa L.	Not specified	Not specified	Hokkaido district
Enomoto et al. 1956	7-14		40-45	Oryza Sativa L.	Indica	Kuhei, Kameno, Kisushu, Korolah	
Enomoto et al. 1956				Oryza Sativa L.	Japonica	Fujisaka,Hakkoda,Rikuu132, Norin1, Norin6, Norin22,	
Matsui et al. 2001			41	Oryza Sativa L.	Japonica	Akitakomachi, Nipponbare, Aichinokaore, Yumeikari, Akihikari, Kinmaze, Aoinokaze, Minamihikari, Hinohikari	high temp(35,37,40ºC day-26ºC night)
Matsushima et al. 1964	16	21	36	Oryza Sativa L.	Japonica	Norin25	Air-temp/water temp(36,31,21,16)

Literature source	Tmin (ºC)	Topt (ºC)	Tmax (ºC)	Specie	Sub-specie	Cultivar	Conditions
Ripening (grain filling)							
Welch et al. 2010	20.9		28.2	Oryza Sativa L.	Not specified	Not specified	Tropical or subtropical climate, located in inland plains or larger river deltas
Welch et al. 2010	22.7		31.6	Oryza Sativa L.	Not specified	Not specified	Tropical or subtropical climate, located in inland plains or larger river deltas
Welch et al. 2010	23		31.4	Oryza Sativa L.	Not specified	Not specified	Tropical or subtropical climate, located in inland plains or larger river deltas
Welch et al. 2010	22.7		31.8	Oryza Sativa L.	Not specified	Not specified	Tropical or subtropical climate, located in inland plains or larger river deltas
Welch et al. 2010	23.8		34.1	Oryza Sativa L.	Not specified	Not specified	Tropical or subtropical climate, located in inland plains or larger river deltas
Welch et al. 2010	24.7		31.3	Oryza Sativa L.	Not specified	Not specified	Tropical or subtropical climate, located in inland plains or larger river deltas
Welch et al. 2010	22.8		31.1	Oryza Sativa L.	Not specified	Not specified	Tropical or subtropical climate, located in inland plains or larger river deltas
Vergara 1976	21.1			Oryza Sativa L.	Indica	Datakan	
Vergara 1976	21.3			Oryza Sativa L.	Japonica	Tainan3	
Vergara 1976	21.3			Oryza Sativa L.	Indica	IR8	
Vergara 1976	21.1			Oryza Sativa L.	Indica	IR5	
Vergara 1976	21.1			Oryza Sativa L.	Indica	C4-C63	
Osada et al, 1973	16.2	22.7	29.8	Oryza Sativa L.	Japonica	RD1	Fiels trials in Bangkhen Rice
Osada et al. 1973				Oryza Sativa L.	Indica	IR8	
Aimi et al. 1959	17	21		Oryza Sativa L.	Japonica	Norin29	Chambers at 17,21,25ºC
Matsushima & Manaka 1957	20-21	22	31-32	Oryza Sativa L.	Not specified	Not specified	

Literature source	Tmin (ºC)	Topt (ºC)	Tmax (ºC)	Specie	Sub-specie	Cultivar	Conditions
Matsushima & Tsunoda 1957		31		Oryza Sativa L.	Not specified	Not specified	
Lee 1979	17			Oryza Sativa L.	Japonica	Jinheung	Cold test at Suweon
Lee 1979				Oryza Sativa L.	Hybrid	Tongil,Yushin suweon264, Milyang29	
Ohta & Kimura 2007			28	Oryza Sativa L.	Not specified	Not specified	
Chang 1976			37	Oryza Sativa L.	Not specified	Not specified	
Sato 1973		20		Oryza Sativa L.	Japonica	Norin17	Controlled different temperatures-16 h, photop.
Sato 1973		30		Oryza Sativa L.	Indica	IR8	Controlled different temperatures-16 h, photop.
Yoshida 1981	12-18	20-25	30	Oryza Sativa L.	Not specified	Not specified	
Whole plant							
Baker 2004		28	36	Oryza Sativa L.	Japonica	Cocodrie, Cypress, Jefferson	Growth chambers at constant day-night air temperature(24,28,32, 36,40ºC)
Yoshida 1981	<20		>30	Oryza Sativa L.	Not specified	Not specified	
Huke 1976	15	23.3-27.7	33.8-39	Oryza Sativa L.	Not specified	Not specified	
Huke 1976	17.7-22.7		28-34	Oryza Sativa L.	Not specified	Not specified	
Grover et al. 2009		23-31		Oryza Sativa L.	Not specified	Not specified	
Vergara 1976	10-21			Oryza Sativa L.	Not specified	Not specified	
Chung 1979	8	15-25	30	Oryza Sativa L.	Not specified	Not specified	Regions of Suweon and Jaecheon (Korea)
Nakagawa et al, 2003		35		Oryza Sativa L.	Not specified	Not specified	
Alocilja et al. 1991	8		42	Oryza Sativa L.	Not specified	Not specified	
Kropff et al. 1994	8	30	42.5	Oryza Sativa L.	Not specified	Not specified	

Table A1.4. Lethal temperature limits for maize

Litterature source	Tmin (ºC)	Conditions	Tmax (ºC)	Conditions
CJ Birch et al. 1998a			44	Field trial Australia
Harper 1956	0	Pretreated above 20 C seeds		
Ramadoss et al. 2004				
CJ Birch et al 1998c	0	Temperate and tropical regime	44	Field trials Holland and Mexico
Sinsawat et al. 2004			45	In vitro exposed to heatstress
Lehenhauer 1914			42.7	
Carter & Hestmen 1990	-2.2	Temperate and tropical		
Sinsawat et all 2004			50	In vitro grown at high temperature
Brooking 1990			50	
Harper 1956	0	Pretreated seeds 20 C		
Buican 1969	-6	Seedlings		
Buican 1969	-2	Seedlings		
Rahn & brown 1971	-3	Vegetative stage		
Rahn & Brown 1971	-1.5	Vegetative stage		

Table A1.5. Base (Tmin), optimum (Topt) and maximum (Tmax) cardinal temperatures for different key growth processes in maize

Literature source	Tmin (ºC)	Topt (ºC)	Tmax (ºC)	Absolute production or growth rates	Cultivar	Conditions
Leaf initiation						
Warrington & Kanemasu 1983b	4	31		1.05 leaves/day	W346, XL45	Controlled conditions of 17 regimes day/night temp from 16/6 to 38/33
Tollenaar 1979	6	31.5			Stewart 2300; Trojan TX68; United 106; PAG SX42; Pioneer 3911; United 132	
Swan et al.1981	9	28.5	40			
Barlow 1977	12.5	28			Pride 5	Growth chamber at soil temp 10-28 C (air temp. constant 27.5)
Ben-Haj-Salalh 1995	9.8	31				Growth cabinets and fieldtriel
Fournier & Andreieu 1998	8	31				
Warrington & Kanemasu 1983b	2	31.7		0.433 d-1	W346, XL45	
Tollenaar et al. 1979	6	31.5		0.581 d-1	Stewart 2300; Trojan TX68; United 106; PAG SX42; Pioneer 3911; United 132	Growth cabinets at constant day/night temp from 10 to 35 C, and also 16 regimes of differential day/night temp. Both 15 hour Photoperiod
CJ Birch et al. 1998b	8	34	40		Wageningen: LG22.42; LG11; Lincoln; Hycorn 42 Texas: De kalb 656; Pioneer C41; Mexico: Pool 16 C20, PR 8330, Across 8328 BN 6, La Posta Sequia C4, CML246; CML243.	In vivo Field Experiment Wageningen , Shading Experiment Texas, Field conditions Low land tropics Mexico
Coligado & Brown 1975		30		1.4-1 .6 leaves/day	United 108; Guelph GX122	
Kim et al. 2007		31	44	0.5	Pioner hybrid 3733	Controlled conditions
Kim et al. 2007		34			Pioner hybrid 3733	Controlled conditions (Phyllochrome rate)
Shoot growth						
Lehenhauer 1914		31	42.7			Field trials (soil temperature)
Blacklow 1972	9	30	40			
Walker 1969	12	31	35			
Allmaras 1964	12.7	32.2	37.7		Hybrid	Greenhouse experiment soil temperature from 55

Literature source	Tmin (ºC)	Topt (ºC)	Tmax (ºC)	Absolute production or growth rates	Cultivar	Conditions
						to 100 F
Birch et al. 2002	9.8					
Root growth						
Hund et al. 2008	13	24			14 inbreed lines	Growth chambers at air/soil temp. 15/13 17/13 24/20
Lehenhauer 1914			42			Fixed soil and air temperature
Allmaras 1964	12.7	27.38	43.3			Field trials
Walker 1969	12	26	35		Stewart 2300; Trojan TX68; United 106; PAG SX42; Pioneer 3911; United 132	23 day old seedling grown at soil temperatures 12 – 35 C
Mackay and Barber 1984		25				
Pahlavanian & Silk 1988		29		30 – 35 ug dry weight mm /h	WF9 mol 17	Growth champer at 16, 19, 24 and 29 C

Table A1.6. Base (Tmin), optimum (Topt) and maximum (Tmax) cardinal temperatures for key phenological phases and development stages in maize

Literature source	Tmin (ºC)	Topt (ºC)	Tmax (ºC)	Cultivar	Conditions
Sowing to emergence					
Itabari et al. 1993	6.1	33.6	42.9	Kenyan cultivars	In vitro + field trials
Riley 1984	10	28	37	Maris Jade	In vitro
Nield & Richman 1981	12.7				
Akman 2009			41		
CIMMYT 2010			40		
Eagels and Hardacre 1979	11			US cornbelt hybrids	
Farooq et al 2008		27		Hycorn 8288	Controlled
Warrington and Kanemasu 1983 a	8.9	30		XL45 W346	
Eagels and Hardacre 1980	13			US cornbelt hybrids	
Hodges 1991	10				
Warrington and Kanemasu 1983 a	8	28			
Sowing to tassel initiation					
Coligado & Brown 1975	15	25		United 108, Guldph GX122	3 different photoperiods and temperatures 10-30
CJ Birch et al 1998a	8	34	40	Pacific Hycorn 42, De Kalb DK 529, DE Kalb XL 82, Pacific Hycorn 83, QDPI Barker	
Soldati et al. 1999	16	30		4 tropical varieties	
CJ Birch et al. 2003	8.3				
Warrington and Kanemasu 1983 a-c	8			XL45 W346	
Ellis et al. 1992	9.4	25.3	38.2		Five cultivars (temperate, tropical and subtropical)
Elis et al. 1992b	9.5	31	39.2	Tuxpeno Crema 1C 18	
Elis et al. 1992b	10.2	22		Across 8201	
Elis et al. 1992b	8.4	25	39.3	Cravinhos 8445	
Elis et al. 1992b	9.4	19–22		B73 x Mo17	
Elis et al. 1992b	9.5	31	39.2	H-32	
Tollenaar et al. 1979	6	31		See table 3	
Warrington and Kanemasu 1983 a	7			XL45 W346	
Derieux & Bonhomme 1982	8.5			11 hybrids	Field trials Europe
Bonhomme et al. 1994a	6				Multisite temperate and tropical cultivars
Anthesis					
Warrington and Kanemasu 1983 a	7	28			
Birch et al. 1998c	8	34			
Birch et al. 2003	8				

Literature source	Tmin (ºC)	Topt (ºC)	Tmax (ºC)	Cultivar	Conditions
Ramadoss et al. 2004			38	Pioneer- C87	Hot dry
Nield 1982			35		
Carberry et al. 1989			38	XL82	
Herrero & Johnson 1980		29.5	38		In vitro temp 27, 32 and 38
Ripening (grain filling)					
Broking 1993	10	24.7		Pioneer P3901; Pioneer 3709	Field trial, Temperate maritime environment,
Jones & Kinnery 1986	6	26			
Ramadoss et al. 2004			38	Pioneer- C87	Hot dry, Field trial Queensland Australia
Carberry et al. 1989		30		XL82	
Duke & Doehlert 1996		25	35	B73xMol7	In vitro temp 25-35
Nield 1982			35		
Whole plant					
Shaykewich CF 1994	6	30	44		
Yan and Hunt 1999		31.4	41		
Allmaras 1964		31	39.8		Soil temperature
Arnold 1974	7	27			
Lehenhauer 1914)	5	31	42.7		
Margetts 1985	5.8	31.8	40		
Wang 1960			40		
CJ Birch et all 2003	8				
Lehenhauer 1914)	5		43		
Brooking 1990	8		50	High input semiarid	
Yin et al. 1995		32	37	H-32, Across 8201	
Sinsawat et all 2004			45-50	Penjalihan	Seedlings grown at 25 or 41 C
Olsen et al. 1993	5.9	32.3	40	In vitro 9 commercial cultivars	
CIMMYT 2010	5		45		

Table A1.7. Summary of mean (±se) of: lethal minimum (TLmin) and lethal maximum (TLmax) temperatures; base (Tmin), optimum (Topt) and maximum (Tmax) temperatures for relevant processes and development phases in wheat from Porter & Gawith (1999)

Processes		Wheat Mean Temperature (±se)(ºC)
Lethal Limits	TLmin	-17.2 (1.2)
	TLmax	47.5 (0.5)
Leaf initiation	Tmin	-1 (1.1)
	Topt	22.0 (0.4)
	Tmax	24.0 (1.0)
Shoot growth	Tmin	3.0 (0.4)
	Topt	20.3 (0.3)
	Tmax	>20.9 (0.2)
Root growth	Tmin	2.0
	Topt	<16.3 (3.7)
	Tmax	>25.0 (5.0)
Phenological phases		
Anthesis	Tmin	9.5 (0.1)
	Topt	21.0 (1.7)
	Tmax	31.0
Grain filling	Tmin	9.2 (1.5)
	Topt	20.7 (1.4)
	Tmax	35.4 (2.0)

References included in Annex 1

Adachi K, Inouye J (1972) Effects of photo-period, light intensity and components of culture medium on flower initiation in highly thermo-sensitive paddy rice plants. Proceedings of the Crop Science Society of Japan, 41, 78-82

Aimi R, Sawamura H, Konno S (1959) Physiological studies on the mechanism of crop plants. The effect of the temperature upon the behavior of carbohydrates and some related enzymes during the ripening of rice plant. Proceedings of the Crop Science Society of Japan, 27, 405-407

Akman Z, (2009) Comparison of high temperature tolerance in maize, rice and sorghum seeds by plant growth regulators. Journal of Animal and Veterinary Advances 8, 358-361

Allmaras RR, Burrows WC, Larson WE (1964) Early Growth of as affected by soil temperature. Soil Science, 271–275

Alocija EC, Ritchie JC (1991) A model for the phenology of rice. In: Predicting crop phenology (ed Hodges T). CRC Press, Boca Raton, Florida, pp. 181-189

Arnold CY (1974) Predicting stages of sweet corn (Zea mays L.) development. Journal of the American Society for Horticultural Science, 99, 501–505

Baker JT (2004) Yield responses of southern US rice cultivars to CO_2 and temperature. Agricultural and Forest Meteorology, 122, 129-137

Baker JT, Allen LH Jr, Boote KJ (1992) Response of rice to carbon dioxide and temperature. Agricultural and Forest Meteorology, 60, 153-166.

Barlow EWR, Boersma L, Young JL (1977) Photosynthesis, transpiration, and leaf elongation in corn seedlings at suboptimal soil temperatures. Agronomy Journal, 69, 95-100

Birch CJ, Andrieu B, Fournier C (2002) Dynamics of internode and stem elongation in three cultivars of maize. Agronomie 22, 511-524

Birch CJ, Hammer GL, Rickert KG (1998) Temperature and photoperiod sensitivity of development in five cultivars of maize (Zea mays L.) from emergence to tassel initiation. Field Crops Research, 55, 93-107

Birch CJ, Hammer GL, Rickert KG (1998c) Modelling leaf production and crop development in maize (Zea mays L.) after tassel initiation under diverse conditions of temperature and photoperiod. Field Crops Research, 58, 81-95

Birch CJ, Vos J, Van der Putten PEL (2003) Plant development and leaf area production in contrasting cultivars of maize grown in a cool temperate environment in the field. European Journal of Agronomy, 19, 173-188

Birch CJ, Vosb J, Kiniryc J, Bosb HJ, Elings A (1998b) Phyllochron responds to acclimation to temperature and irradiance in maize. Field Crops Research, 59, 187-200

Blacklow WM (1972b) Influence of temperature on germination and elongation of the radicle and shoot of corn (Zea mays L.). Crop Science, 12, 647-50

Bonhomme R, Derieux M, Edmeades GO (1994) Flowering of diverse maize cultivars in relation to temperature and photoperiod in multilocation fields trials. Crop Science 34, 156-164

Brooking IR (1990) Maize ear moisture during grain-filling and its relation to physiological maturity and grain-drying. Field Crops Res, 23, 55–68

Brooking IR (1993) Effect of temperature on kernel growth rate of maize grown in a temperate marine environment. Filed crop Research, 35, 135-145

Burton JD, Gronwald JW, Somers DA, Gengenbach BG, Wyse DL (1989) Inhibition of corn acetyl-COA carboxylase by cyclohexanedione and aryloxyphenoxypropionate herbicides. Pestic Biochem Physiol, 34, 76-85

Carberry PS, Muchow RC, McCown RL (1989) Testing the CERES-maize simulation model in a semi-arid tropical environment. Field Crops Research, 20, 297-315

Carter PR, Hesterman OB (1990) Handling corn damage by autumn frost. Climate & Weather. Purdue University Cooperative Extension Service. Available at: http://www.ces.purdue.edu/extmedia/NCH/NCH-57.html

Chang TT, Oka HI (1976) Genetic variousness in the climatic adaptation of rice cultivars. In: Adaptability of rice varieties to climate. Proceedings of the symposium on climate and rice. International Rice Research Institute, Los Baños, Philippines, pp. 87-109

Chaudhary TN, Ghildyal BP (1969) Germination response of rice seeds to constant and alternating temperatures. Agronomy Journal, 61, 328-330

Chaudhary TN, Ghildyal BP (1970a) Effect of temperature associated with levels of bulk density on rice seedling emergence. Plant and Soil, 33, 87-91

Chaudhary TN, Ghildyal BP (1970b) Influence of submerged soil temperature regimes on growth, yield, and nutrient composition of rice plant. Agronomy Journal, 62, 281-285

Chung GS (1979) The rice cold tolerance program in Korea. In: Report of a rice cold tolerance workshop. International Rice Research Institute, Los Baños, Philippines, pp 7-19

CIMMYT (2010) Proceedings of the 10th Asian Regional Maize Workshop. International Maize and Wheat Improvement Centre

Coligado MC, Brown DM (1975) Response of corn (Zea Mays L.) in the pre-tassel initiation period to temperature and photoperiod. Agricultural Meteorology, 14, 357-367

Derieux M, Bonhomme R (1982) Heat unit requirements for maize hybrids in Europe, results of the European fao sub-network I. Sowing-silking period. Maydica, 27, 59-77

Dingkuhn M, Sow A, Samb A, Diack S, Asch F (1995) Climatic determinants of irrigated rice performance in the Sahel I. Photothermal and micro-climatic responses of flowering. Agricultural Systems, 48, 385-410

Duke ER, Doehlert DC (1996) Effects of heat stress on enzyme activities and transcript levels vs developing maize kernels grown in culture. Environmental and Experimental Botany, 36, 199-208

Eagles HA, Hardacre AK (1979) Genetic variation in maize (Zea Mays) for germination and emergence at 10^{o} C°. Euphytrica, 28, 287-295

Eagles HA, Hardacre AK (1980) Comparisons Among Population of Maize for Growth at 13ºC. Crop Sciences, 20, 780

Ehrler W, Bernstein L (1958) Effects of root temperature, mineral nutrition, and salinity on the growth and composition of rice. Botanical Gazette, 120, 67-74

Ellis RH, Qi A, Summerfield RJ, Edmeades GO, Roberts EH (1992a) Photoperiod, Temperature, and the Interval from Sowing to Tassel Initiation in Diverse Cultivars of Maize. Crop Science, 32, 1225-1232

Ellis RH, Qi A, Summerfield RJ, Edmeades GO, Roberts EH (1992b) Photoperiod, Leaf Number, and Interval from Tassel Initiation to Emergence in Diverse Cultivars of Maize. Crop Science, 32, 398-403

Ellis RH, Qi A, Summerfield RJ, Roberts EH (1993) Rates of leaf appearance and panicle development in rice (Oryza sativa L.): a comparison at three temperatures. Agricultural and Forest Meteorology, 66, 129-138

Enomoto N, Yamada I, Hozumi K (1956) On the artificial germination of pollen in rice plants. Temperature limits of pollen germination in rice varieties. Proceedings of the Crop Science Society of Japan, 25, 69

Fadzillah NM, Gill V, Finch RP, Burdon RH (1996) Chilling, oxidative stress and antioxidant responses in shoot cultures of rice. Planta, 199, 552-556

Farooq M, Aziz T, Basra SMA, Cheema MA, Rehman H (2008) Chilling Tolerance in Hybrid Maize Induced by Seed Priming with Salicylic Acid. Journal of Agronomy and Crop Science

Fournier C, Andrieu B (1998) A 3D Architectural and Process-based Model of Maize Development. Annals of Botany, 81, 233-250

Gao L, Jin Z, Huang Y, Zhang L (1992) Rice clock model: computer model to simulate rice development. Agricultural and Forest Meteorology, 60, 1-16

Grover A, Katiyar-Agarwal S, Agarwal M, Sahi C, Agarwal S, Chandramouli A (2009) Abiotic stress tolerance in rice. In: Rice improvement in the genomics era. International Rice Research Institute, CRC Press, Boca Raton, Florida, pp. 237-268

Hamdani AR (1979) Low-temperature problems and cold tolerance research activities for rice in India. In: Report of a rice cold tolerance workshop. International Rice Research Institute, Los Baños, Philippines, pp. 39-48

Han F, Chen H, Li X, Yang M, Liu G, Shen S (2009) A comparative proteomic analysis of rice seedlings under various high-temperature stresses. Biochimica Et Biophysica Acta, 1794, 1625-1634

Harper JL (1956) Studies in seed and seedling mortality. Direct and indirect influences of low temperatures on the mortality of maize. New Phytol, 55, 35-44

Herath W, Ormrod DP (1965) Some effects of water temperature on the growth and development of rice seedlings. Agronomy Journal, 57, 373-376

Herrero MP, Johnson RR (1980) High temperature stress and pollen viability in maize. Crop Science, 20, 796–800

Hodges T (1991) Temperature and water stress effects on phenology. In: Predicting crop phenology (ed Hodges T). CRC Press, Boca Raton, Florida, pp 7-13

Hoshino T, Matsushima S, Tomita T, Kikuchi T, Sadakane A (1969) Analysis of yield-determining process and its application to yield-prediction and culture improvement of lowland rice. Combined effects of air-temperature and water-temperature in seedling periods on the characteristics of seedlings of rice plant. Proceedings of the Crop Science Society of Japan, 38, 273-278

Huke R (1976) Geography and climate of rice. In: Climatic environment of rice cultivation. Proceedings of the Symposium on Rice and Climate. International Rice Research Institute, Los Baños, Philippines, pp. 31-50

Hund A, Fracheboud Y, Soldati A, Stamp P (2008): Cold tolerance of maize seedlings as determined by root morphology and photosynthetic traits. European Journal of Agronomy, 28, 178–185

Itabari JK, Gregory PJ, Jones RK (1993) Effects of temperature, soil water status and depth of planting on germination and emergence of maize (Zea Mays) adapted to semi-arid eastern Kenya. Experimental Agriculture, 29, 351-364

Jagadish S, Craufurd P, Wheeler T (2007) High temperature stress and spikelet fertility in rice (Oryza sativa L.). Journal of Experimental Botany, 58, 1627-1635

Jones CA, Kiniry JR (1986) CERES-maize: a simulation model of maize growth and development. Texas A&M University Press, College Station

Khan AA, Seshu DV (1987) Using ethylene to monitor the influence of adverse climatic factors and to predict plant performance. In: Weather and rice. Proceedings of the international workshop on the impact of weather parameters on growth and yield of rice. International Rice Research Institute. Los Baños. Laguna. Philippines, pp. 103-122

Kim SH, Dennis CG, Richard CS, Jeffrey TBD, Dennis JT, Vangimalla RR (2007) Temperature dependence of growth, development, and photosynthesis in maize under elevated CO_2. Environmental and Experimental Botany, 61, 224–236

Kiniry JR, Rosenthal WD, Jackson BS, Hoogenboom G (1991) Predicting leaf development of crop plants. (ed Hodges T). CRC Press, United States, pp. 29-42

Kropff MJ, Van Laar HH, Matthews RB (1994) ORYZA1: an ecophysiological model for irrigated rice production. SARP Research Proceedings.

Lee JH (1979): Screening methods for cold tolerance at Crop Experiment Station Phytotron and at Chuncheon. In: Report of a rice cold tolerance workshop. International Rice Research Institute. Los Baños, Philippines, pp. 77-90

Lehenbauer PA (1914): Growth of maize seedlings in relation to temperature. Physiology Researches, 1, 247-288

Livingston BE, Haasis FW (1933) Relations of Time and Maintained Temperature to Germination Percentage for a Lot of Rice Seed. American Journal of Botany, 20, 596-615

Mackay AD, Barber SA (1984) Soil Temperature Effects on Root Growth and Phosphorus Uptake by Corn. Soil Science Society, American Journal, 48, 818-823

Manalo PA, Ingram KT, Pamplona RR, Egeh AO (1994) Atmospheric CO_2 and temperature effects on development and growth of rice. Agriculture, Ecosystems and Environment, 51, 339-347

Margets JC (1985) Crop Scheduling in processing and fresh market sweet corn, Thesis, University of Queensland, Gatton

Matsui T, Omasa K, Horie T (2001) The difference in sterility due to high temperatures during the flowering period among japonica-rice varieties. Plant Production Science, 4, 90-93

Matsushima S, Manaka T (1957) Analysis of developmental factors determining yield and yield prediction in lowland rice. On the mechanism of ripening. Effects of temperatures and light intensities and their compound conditions in different stages in growth upon the ripening of rice plants. Proceedings of the Crop Science Society of Japan, 25, 203-206

Matsushima S, Tanaka T, Hoshino T (1964) Analysis of yield-determining process and its application to yield prediction and culture improvement of lowland rice. Combined effects of air temperatures and water temperatures at different stages of growth on the grain yield and its components in lowland rice. Proceedings of the Crop Science Society of Japan, 33, 53-58

Matsushima S, Tanaka T, Hoshino T (1968) Analysis of yield-determining process and its application to yield prediction and culture improvement of lowland rice. Rooting ability of rice seedlings, which were raised under different air- and water-temperatures, after transplanting. (In the case of seedlings treated for an identical number of days in seedling period. Proceedings of the Crop Science Society of Japan, 37, 161-168

Matsushima S, Tsunoda K (1957): Analysis of developmental factors determining yield and yield prediction in lowland rice. On the mechanism of ripening. Effects of the range of daily temperature in different stages in growth upon the ripening of rice plants. Proceedings of the Crop Science Society of Japan, 25, 203-206

Matsushima S, Tsunoda K (1958) Analysis of developmental factors determining yield and its application to yield prediction and culture improvement in lowland rice. Effects of temperature and its daily range in different growth stages upon the growth, grain yield and its constitutional factors. Proceedings of the Crop Science Society of Japan, 26, 243-244

Mitchell PL, Sheehy JE (2000) Performance of a potential C_4 rice: overview from quantum yield to grain yield. In: Redesigning rice photosynthesis to increase yield (eds Sheehy JE, Mitchell PL, Hardy B). International Rice Research Institute, Los Baños, Philippines, pp. 145-163

Murakami T (1987) Analytical studies on the planning of time-scheduled rice cultivation. Japan Agricultural Research Quarterly, 21, 1-7

Nakagawa H, Horie T, Matsui T (2003) Effects of climate change on rice production and adaptive technologies. In: Rice science: innovations and impact for livelihood.

Proceedings of the International Rice Research Conference, pp 635-658. International Rice Research Institute. Beijing, China

Neild R.E, Richman NH (1981) Agroclimnatic normals for maize. Agricultural Meteorology, 24, 83-95

Neild RE (1982) Temperature and rainfall influences on the phenology and yield of grain sorghum and maize: A comparison. Agricultural Meteorology, 27, 79-88

Nishiyama I (1976) Effects of temperature on the vegetative growth of rice plants. In: Enviromental control of growth and yield. Proceedings of the Symposium on Rice and Climate, pp 159-185. International Rice Research Institute. Los Baños, Philippines

Oda Y, Honda T (1963) Environmental control of tillering in rice plants. Reports of the Institute for Agricultural Research Tohoku University, 14, 15-36

Ohta S, Kimura A (2007) Impacts of climate changes on the temperature of paddy waters and suitable land for rice cultivation in Japan. Agricultural and Forest Meteorology, 147, 186-198

Oka H (1954) Intervarietal differences in the minimum temperature for germination and the temperature constant of rice grains. Phylogenetic differentiation of cultivated rice. Japanese Journal of Breeding, 4, 140-144

Olsen JK, McMahon CR, Hammer GL (1993) Prediction of sweet corn phenology in subtropical environment. Agronomy Journal, 85, 410-415

Osada A, Nara M, Chakrabandhu H, Rahong M, Gesprasert M (1973) Seasonal changes in growth pattern of tropical rice. Environmental factors affecting yield and its components. Proceedings of the Crop Science Society of Japan. 42, 351-361

Owen PC (1971) The effects of temperature on the growth and development of rice. Field Crop Abstracts, 24, 1-8

Pahlavanian AM, Silk WK (1988) Effect of Temperature on Spatial and Temporal Aspects of Growth in the Primary Maize Root. Plant Physiology, 87, 529-532

Puteh AB, Roziah R, Mohamad RB (2010): Dormancy and cardinal temperatures during seed germination of five weedy rice (Oryza spp.) strains. Journal of Tropical Agricultural Science. 33, 243-250

Rahn JJ, Brown D (1971) Estimating corn canopy extreme temperatures from shelter values. Agricultural Meteorology, 8, 129-138

Ramadoss M, Colin JB, Carberry PS, Robertson M (2004) Water and high temperature stress effects on maize production. 4th international crop science congress

Riley J (1984) A general form of the “land equivalent radio”. Experimental Agriculture, 20, 19-29

Roberts EH, Carpenter AJ (1965) The interaction of photoperiod and temperature on the flowering response of rice. Annals of Botany, 29, 359-364

Salah BH, Tardieu H, Tardieu F (1995) Temperature effects expansion rate of maize leaves without change in spatial distribution of cell length: analysis of the coordination between cell division and cell expansion. Plant Physiology, 109, 861-870

Satake T, Hayase H (1970) Male sterility caused by cooling treatment at the young micro-spore stage in rice plants. Estimations of pollen developmental stage and the most sensitive stage to coolness. Proceedings of the Crop Science Society of Japan, 39, 468-473

Satake T, Yoshida S (1978) High temperature-induced sterility in indica rices at flowering. Japanese Journal of Crop Science, 47, 6-17

Sato K (1972) Growth responses of rice plants to environmental conditions. The effects of air temperatures on growth at the vegetative stage. Proceedings of the Crop Science Society of Japan, 41, 388-393

Sato K (1973) The development of rice grains under controlled environment. Germinability of seeds ripened under different environmental conditions. Tohoku Journal of Agricultural Research, 24, 14-21

Shahi BB, Heu MH (1979) Low-temperature problem and research activities in Nepal. In: Report of a rice cold tolerance workshop. International Rice Research Institute, Los Baños, Philippines, pp. 61-68

Shaykewich CF (1994) An appraisal of cereal crop phenology modelling. Canadian Journal of Plant Science, 329–341

Shibata M (1979) Progress in breeding cold-tolerant rice in Japan. In: Report of a rice cold tolerance workshop. International Rice Research Institute, Los Baños, Philippines, pp. 21-24

Shimizu M, Kuno K (1966) Studies on the morphogenic abnormalities in rice spikelets caused by a low temperature. Proceedings of the Crop Science Society of Japan, 35, 91-99

Sie M, Dingkuhn M, Wopereis MCS, Miezan KM (1998) Rice crop duration and leaf appearance rate in a variable thermal environment. Development of an empirically based model. Field Crops Research, 57, 1-13

Sinsawat V, Leipner J, Stamp P, Fracheboud Y (2004) Effect of heat stress on the photosynthetic apparatus in maize (Zea mays L.) grown at control or high temperature. Environmental and Experimental Botany, 52, 123–129

Soldati A, Stehli A, Stamp P (1999) Temperature adaptation of tropical highland maize (Zea mays L.) during early growth and in controlled conditions. European Journal of Agronomy, 10, 111–117

Swan D, Brown DM, Coligado MC (1981) Leaf emergence rates of corn (Zea mays L.) as affected by temperature and photoperiod. Agricultural Meteorology, 24, 57-73

Tollenar M, Danard TB, Hunter RB (1979) Effect of temperature on rate of leaf appearance and flowering date in maize. Crop Science, 19, 363–370

Ueki K (1960) The influence of temperature of irrigation water upon the growth of paddy rice in the warmer district. The injuries due to high water temperature on development of young panicle. Proceedings of the Crop Science Society of Japan, 29, 75-78

Ueki K (1966) The influence of temperature of irrigation water upon the growth of paddy rice in the warmer district. Effects of day and night water-temperatures on the vegetative growth in relation to air temperature change accompanied with shifting of cultivation period. Proceedings of the Crop Science Society of Japan, 35, 8-12

Vergara B.S (1976) Physiological and morphological adaptability of rice varieties to climate. In: Adaptability of rice varieties to climate. Proceedings of the Symposium on Rice and Climate. International Rice Research Institute, Los Baños, Philippines, pp. 67-83

Vergara BS, Chu TM, Visperas RM (1970) Effect of temperature on the anthesis of IR8. International Rice Commission Newsletter, 19, 11-17

Walker JM (1969) One-degree increments in soil temperatures affect maize seedling behavior, proceedings. Soil Science Society of America, 33, 729 736

Wang D, Portis AR Jr, Moose PS, Long SP (2008) Cool C4 Photosynthesis - Pyruvate Pi Dikinase Expression and Activity Corresponds to The Exceptional Cold Tolerance of Carbon Assimilation in Miscanthus x giganteus. Plant Physiology, pp. 108

Warrington IJ, Kanemasu ET (1983a) Corn growth response to temperature and photoperiod I. Seedling emergence, Tassel initiation and Anthesis. Agronomy Journal, 75, 749-754

Warrington IJ, Kanemasu ET (1983b) Corn growth response to temperature and photoperiod II. Leaf-initiation and leaf appearance. Agronomy Journal, 75, 755 -761

Warrington IJ, Kanemasu ET (1983c) Corn growth response to temperature and photoperiod III. Leaf number. Agronomy Journal, 75, 762 -766

Welch JR, Vincent JR, Auffhammer M, Moya PF, Dobermann A, Dawe D (2010) Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. Proceedings of the National Academy of Sciences, 107, 14562-14567

Yamakawa Y, Kishikawa H (1957) On the effect of temperature upon the division and elongation of cells in the root of rice plant. Proceedings of the Crop Science Society of Japan, 26, 94-95

Yan W, Hunt LA (1999) An equation for modelling the temperature response of plants using only the cardinal temperatures. Annals of Botany, 84, 607-614

Yin X, Kropff L, Martin J, McLaren G, Visperas RM (1995) A nonlinear model for crop development as a function of temperature. Agricultural and Forest Meteorology, 77, 1-16

Yin XinYou, Kropff MJ (1996a) The Effect of Temperature on Leaf Appearance in Rice. Annals of Botany, 77, 215-221

Yin XinYou, Kropff MJ (1996b) Differential effects of day and night temperature on development to flowering in rice. Annals of Botany, 77, 203-213

Yoshida S (1981): Fundamentals of rice crop science. Laguna International Rice Research Institute. Los Banos, Philippines, pp. 269

Annex 2. Guidelines for the interviews and summary of the responses

Guidelines for the interviews

Objective of the research

Coastal systems in the North-east Atlantic Ocean are expected to experience adverse impacts due to projected sea-level rise and climate change. There is a need to improve the planning by assessment of coastal vulnerability and flexible adaptation from the local scale and engage widely with relevant stakeholders.

The main goal of this research is to assess the climate change risk and what are the potential adaptation options in the Doñana coastal wetlands, a world heritage and biodiversity site with an intensive agricultural activity under scarcity conditions. We aimed to contribute to adaptation plans development in the case study region including the participation of informed stakeholders. The research was completed within the Spanish Biodiversity Foundation project of Adaptation in Doñana, implemented and coordinated by WWF-Spain.

Methodology

The interviews aimed to draw a broad outline of the case study's vulnerability based on the expertise and knowledge of local actors and develop a range of flexible adaptation options according to the local environmental, social and policy context.

The interview survey was conducted across different days in February 2012 and eleven key participants from relevant sectors of the coastal wetland were encouraged to give their input. The requirements for the participants' selection were: i) to be working on activities related to the rice production and the natural ecosystem during the last decade; ii) to have an extensive knowledge about the rice productive sector and to have regular contact with the rice farmers; ii) to have an extensive knowledge about the welfare of the wetland and the natural ecosystem functioning; and iii) to be informed on the water management requirements to cope successfully with the rice production and the natural ecosystem.

Interview questions

Type of question	Selected interview question
Introduction	Q1: Name Q2: Background and experience in the region Q3: Employment status
Perception of climate change risks/impacts for the rice farming and the natural ecosystem	Q4: Do you feel that the Doñana socio-environmental system has changed due to climate variability or extreme events (droughts, heat waves, rainfall distributions) over the last 20 years? (E.g. severe droughts of 1979/80, 1991/95 or 2004/05)? Q5: Have you noticed changes in the yields or the growing cycle (shortening/lengthening) of rice crops in the wetland? Q6: Have you noticed changes in the presence or occurrence of pests, weeds and diseases? Q7: Have you noticed changes in the management (e.g. operations, irrigation, use of fertilizers/sprays) of rice crops? Q8: Have you noticed river hydro morphological alterations or changes in the water availability and quality (e.g. salinity of water) in the region? Q9: Have you noticed changes in the distribution of natural vegetation and wildlife? Q10: What factor do you consider as the most harmful for the rice farming and the natural ecosystem in the region?
Perception of flexible adaptation options for the rice farming and the natural ecosystem	Q11: What measures have been implemented to tackle climate variability and climate change? Q12: What strategies have been implemented to ensure water availability? Q13: What importance do you consider that may have strategies to increase water savings? Q14: What adaptation options do you consider the most effective for the rice farming and the natural ecosystem in the region? Q15: What are the main drivers and tools to undertake these adaptation measures and strategies? Q16: What are the main barriers to the implementation of climate change adaptation options in the region?
Other comments	Q17: Are there any other issues that you consider important in relation to the climate change risks and adaptation which have not tried yet in this interview?

Table A2.1 Summary of the responses of the interviews

Identification of risks and adaptation options	Farmer association (5)	Administration (3)	Environmentalists (3)
Main risk for the artificial rice wetland	Decreased water availability	Decreased water availability	Decreased water availability
	Increased water salinity	Increased water salinity	Increased water salinity
	Higher temperatures	Higher temperatures	
		Reductions of water stored	
		Heavy rains and higher deposits appearance	
Most effective adaptation, overall	Changes of water management	Water saving	Energy and water savings
	Modernization of irrigation systems	Increased scientific research, field studies and transferring	Increased scientific research, field studies and farmers training
	Water recirculation and reutilization within the paddy	Improved coordination between institutions, aggregated of the information and dissemination	Strategies to conserve biodiversity and ensure the provision of ecosystem services
	New dams construction and other water infrastructures	Improved monitoring and information on water use	Regulations from WFD and the Hydrologic Plan of the Guadalquivir River Basin
		Reduction of the cultivated areas located closer to the sea	Long-term climate change strategies and agreements
		Increased the technical efficiency of the irrigation systems	Increased dissemination, public participation and environmental awareness raising
		Local climate change actions	Organic agriculture
		Dikes construction to contain marine intrusion	
Responsible for implementing adaptation	Administration; rice farming unions and cooperatives	Administration; Rice farming unions and cooperatives; Research groups to facilitate	Administration; Rice farming unions and cooperatives; Research groups to facilitate
Barriers to implement adaptation	The lack of clear actions	Rice farming conservative traditions	Rice farming conservative traditions
	Larger reductions of inputs (water, fertilizers, sprays)	The difficult for generational renewal and change due to aging farmers' population	The difficult for generational renewal and change due to aging farmers' population
	Marine intrusion during drought periods	Farmers' short-term perception of risks and profit-driven principles	Farmers' short-term perception of risks and profit-driven principles
	New CAP environmental requirements	The lack of interest of rice farmers in climate change issues and debates	The lack of interest of rice farmers in climate change issues and debates
	Energy prices	Easy crop management, all the operations are subcontracted	Low labour needs and high water comsuption

Identification of risks and adaptation options	Farmer association (5)	Administration (3)	Environmentalists (3)
	Lower yields and quality crops	High subsidies dependence	The lack of environmental awareness
	Irrigation water costs	Clay soils, risks of floods	New CAP environmental requirements
	Extremely competitive an d highly volatile price sector	The unstable equilibrium of the Doñana system	The lack of accurate irrigation water measures (flow meters)
Risks related to water scarcity	Water availability reductions	Water availability reductions	Water availability reductions
	Turbidity, muddy water	Turbidity, muddy water	Water stored reductions
	Cumulative impacts in the Guadalquivir River Basin affect the rice fields		Cumulative impacts in the Guadalquivir River Basin affect the rice fields
	Erosion problems		
Adaptation to increased water scarcity	Changes of water management	Changes of water management	Changes of water management
	Modernization of irrigation systems	Modernization of irrigation systems	Water saving strategies
	Water recirculation and reutilization within the paddy	Water recirculation and reutilization within the paddy	Water recirculation and reutilization within the paddy
	Laser levelling	Installation of flow meters	Modernization of irrigation systems avoiding new water infrastructures with environmental impact
	New dams construction and other water infrastructures		Efficient solutions for both the rice farming and the natural ecosystem
	Setting of irrigation turns		Long-term agreements on water and climate change management (water markets, water use allocation permits)
	Increased farmers training, technical advice and scientific information		Actions at the basin level leading flexible adaptation strategies to climate change
	New rice varieties adapted to water and heat stress		Regulations from WFD and the Hydrologic Plan of the Guadalquivir River Basin
	Installation of flow meters		
	Reduced energy costs		
Perception of the importance of water saving	High	High	High
Risk related to increased salinity	Increased soil salinity	Increased soil salinity	Increased soil salinity
	Increased salinity in the aquifer	Increased salinity in the aquifer	Increased salinity in the aquifer
			Biodiversity losses

Identification of risks and adaptation options	Farmer association (5)	Administration (3)	Environmentalists (3)
Adaptation to increased salinity	Dam water releases upstream from the rice area	Dam water releases upstream from the rice area	Dam water releases upstream from the rice area
	Flooding irrigation systems to wash soils		Organic production (good farming practices)
	New pipeline to bring in the water directly upstream from the salt water intrusion		
Risk related to increased invasive species, pests and diseases	Ineffectiveness of current plant protection products		Biodiversity losses
Adaptation to increased invasive species, pests and diseases	Integrated production	Integrated production	Integrated production
Risk related to decreased rice productivity and quality	Reduction of the rice cultivated areas	Reduction of the rice cultivated areas	Reduction of the rice cultivated areas
	Lower income		
Adaptation to decreased productivity and quality	Changes of the management (integrated production)	Changes of the management (integrated production)	Changes of the management (integrated production)
	New longer cycle rice varieties (J-sendra de 155 or Puntal 145)	Improved commercialization	New varieties but not including those GMOs
	Modernization and innovative technical measures	Farmers training and environmental awareness raising	Farmers training and environmental awareness raising
			Improved the product processed to be exported (organic products)

Annex 3. Guidelines for the interviews

Interview guidelines

Objective of the research

The new policy objectives of European agriculture are to reach a 10% greenhouse gas (GHG) emission reduction by 2020 in Spain and all the EU-27 countries (Decision Nº 406/2009/EC).. There is a need to increase the adoption by farmers of agricultural practices that meet the new policy objectives of GHG emissions mitigation.

The main goal of this research is to assess and prioritise agronomic and soil management practices that have the potential to mitigate GHG emissions while optimizing crop productivity in the region of Aragón. We aimed to contribute to policy development and to transfer the information to farmers' advisory services. The research is being completed within the SmartSOIL project (www.smartsoil.eu) of the 7th Framework Programme of the European Union and with the collaboration of the REMEDIA network (www.remedia.org).

The interviews aimed to draw on the expertise and knowledge of academic experts and develop a prioritization of the mitigation practices which are most suitable to the case study region from social, economic and environmental criteria under two climate scenarios (current climate and a drier and warmer climate scenario).

Methodology

A preliminary selection of potential mitigation practices relevant to the Aragón case study was built on a literature review of previous empirical studies. The method for the prioritization and evaluation of the selected mitigation practices is a Multi-criteria Analysis (MCA). The MCA analyses the experts' priorities given to social, economic and environmental criteria for the implementation of the practices. The data collected from the questionnaires will be input into the software Web-Hipre (http://hipre.aalto.fi/) from the Helsinki University of Technology for multi-criteria evaluation and prioritization.

Filling the tables

We would very much value your input as an expert on the matter. If you would like to participate, please fill the questionnaire using the instructions below. The questionnaire takes about 30 minutes to be answered and is divided in two parts:

1. Assessment of the criteria: allocation of criteria's weights in terms of importance for GHG mitigation and desirability for economic, social and environmental farm benefit (tables C1 y C2).

C1. Please fill the following table and point what is the importance or weight of each criterion to evaluate the mitigation practices suitability (the sum of the weights has to be equal to 100)

Criteria	Weight (%) ∑total = 100
Economic	
Social	
Environmental	

C2. Please fill the following table and point what is the importance or weight of each sub criteria to evaluate the mitigation practices suitability

0 Worst importance level ←→ 10 Best importance level

Criteria	Sub Criteria	Importance weight (0–10)
Economic	CAP subsidies	
	Yield variability	
	Job creation	
	Implementation	
	Economic feasibility	
Social	Rural development	
	Farmer cooperation level	
	Farmer training level	
	Transfer technology	
Environmental	Mitigation potential	
	Soil quality	
	Water quality	
	Ecologic value	

2. Assessment of the six selected mitigation practices: Weight the effect of the mitigation practice adoption against each of the criteria under the two climate scenarios (tables P1, P2, P3, P4, P5 y P6).

Please, weight the effect of implementing the mitigation practice on each sub-criteria following the guidelines below.

Mitigation practices selected to be evaluated:
P1. Cover crops in orchard systems
P2. Reduced tillage / no-tillage
P3. Fertilization with animal manures
P4. Optimized fertilization
P5. Crop rotation
P6. Intercropping

Evaluation guidelines and example:

-100 0 ⟷ +100

Worst negative effect | Neutral effect | Best positive effect

The mitigation practices have to be evaluated by weighting their effect for each criterion under two climate scenarios (current climate scenario and climate change scenario).

The weight scale ranges from -100 to 100, taking into account that -100 represents the worst negative effect of the mitigation practice for the criteria and +100 the best positive effect. The value of 0 is applied when the mitigation practice does not have effect for the criteria.

The two scenarios are classified as a current climate scenario with similar climate conditions to those at present and a climate change scenario with drier and warmer conditions based on the more likely projection according to CEDEX (2011) for Spain (a decrease in average annual rainfall of 8% and an average increase in temperature of 2 degrees Celsius by the 2040s).Example to evaluate a measure: “start a timber industry in the Amazon” with the aim of improve the economic situation of the area.

Criteria	Weight (-100 to +100)	
	Current climate scenario	Climate change scenario
Job creation	60*	60*
Ecologic value	-70**	-90**
Rural development	0***	0***

Reasoning to the weight allocation
(*) Increases of the number of employment rate, regardless of the scenario
(**) Ecological value decreases, especially under warmer conditions
(***) Not significant influence on rural development

P1. Mitigation practice of cover crops in orchard systems

This mitigation measure consists of intercropping spontaneous or human induced cover crops with farmland trees in order to improve soil fertility and water use. It also enhances soil carbon stores thereby increasing the carbon sequestration rate.

Criteria	Weight (-100 to +100)	
	Current Climate scenario	Climate change scenario
CAP subsidies		
Yield variability		
Job creation		
Implementation		
Economic feasibility		
Rural development		
Farmer cooperation level		
Farmer training level		
Transfer technology		
Mitigation potential		
Soil quality		
Water quality		
Ecologic value		
	Weight (0 to 100)	
Overall feasibility		

P2. Mitigation practice of reduced tillage / no-tillage

Reducing or avoiding tillage practices, increase soil carbon storage through reducing microbial decomposition, and promoting crop residue incorporation into soil.

Criteria	Weight (-100 to +100)	
	Current Climate scenario	Climate change scenario
CAP subsidies		
Yield variability		
Job creation		
Implementation		
Economic feasibility		
Rural development		
Farmer cooperation level		
Farmer training level		
Transfer technology		
Mitigation potential		
Soil quality		
Water quality		
Ecologic value		
	Weight (0 to 100)	
Overall feasibility		

P3. Mitigation practice of fertilization with animal manures

Incorporating animal manures to the soil, increases organic carbon stores and enhances carbon return to the soil, thereby encouraging carbon sequestration.

Criteria	Weight (-100 to +100)	
	Current Climate scenario	Climate change scenario
CAP subsidies		
Yield variability		
Job creation		
Implementation		
Economic feasibility		
Rural development		
Farmer cooperation level		
Farmer training level		
Transfer technology		
Mitigation potential		
Soil quality		
Water quality		
Ecologic value		
	Weight (0 to 100)	
Overall feasibility		

P4. Mitigation practice of optimized fertilization

Changes in application rates, fertilizer placement or split applications depending on crop needs increases efficiency thus reducing GHG emissions, especially nitrous oxide.

Criteria	Weight (-100 to +100)	
	Current Climate scenario	Climate change scenario
CAP subsidies		
Yield variability		
Job creation		
Implementation		
Economic feasibility		
Rural development		
Farmer cooperation level		
Farmer training level		
Transfer technology		
Mitigation potential		
Soil quality		
Water quality		
Ecologic value		
	Weight (0 to 100)	
Overall feasibility		

P5. Mitigation practice of crop rotation

Using crop rotations in the same plot, increases soil carbon stores and requires reduced fertilizer use, thereby reducing nitrous oxide emissions.

Criteria	Weight (-100 to +100)	
	Current Climate scenario	Climate change scenario
CAP subsidies		
Yield variability		
Job creation		
Implementation		
Economic feasibility		
Rural development		
Farmer cooperation level		
Farmer training level		
Transfer technology		
Mitigation potential		
Soil quality		
Water quality		
Ecologic value		
	Weight (0 to 100)	
Overall feasibility		

P6. Mitigation practice of intercropping

Combining two crops during the same growing season improves soil fertility and soil carbon storage due to more efficient nutrient use and reducing fertilizers application rate as well as GHG emissions.

Criteria	Weight (-100 to +100)	
	Current Climate scenario	Climate change scenario
CAP subsidies		
Yield variability		
Job creation		
Implementation		
Economic feasibility		
Rural development		
Farmer cooperation level		
Farmer training level		
Transfer technology		
Mitigation potential		
Soil quality		
Water quality		
Ecologic value		
	Weight (0 to 100)	
Overall feasibility		

Annex 4. Regional farm and crop types, and costs and cost effectiveness

Regional farm and crop types

Table A4.1. SEAMLESS farm types and grouping to main farming system

Code	SEAMLESS farm type	Main farming system
1	Arable/Cereal	Field crops
2	Arable/Fallow	Field crops
3	Arable/Specialised crops	Industrial crops
4	Arable/Others	Field crops
5	Dairy cattle/Permanent grass	Pasture and grasslands
6	Dairy cattle/Temporary grass	Pasture and grasslands
7	Dairy cattle/Land independent	Mixed farms
8	Dairy cattle/Others	Mixed farms
9	Beef and mixed cattle/Permanent grass	Pasture and grasslands
10	Beef and mixed cattle/Temporary grass	Pasture and grasslands
11	Beef and mixed cattle/Land independent	Mixed farms
12	Beef and mixed cattle/Others	Mixed farms
13	Sheep and goats/Land independent	Mixed farms
14	Sheep and goats/Others	Mixed farms
15	Pigs/Land independent	Mixed farms
16	Pigs/Others	Mixed farms
17	Poultry and mixed pigs/poultry	Mixed farms
18	Mixed farms	Mixed farms
19	Mixed livestock	Mixed farms
20	Horticulture	Horticulture
21	Permanent crops	Permanent crops

Table A4.2. Distribution of the significant crops and gross margin calculation for the Aragón region in 2011

Crop	Area planted (ha)	Area planted (%)	Yield (tonnes/ha)		Price (€/tonne)		Output (€/ha)	Variable costs (€/ha)	Gross margin (€/ha)
			Crop	Straw	Crop	Straw			
Wheat ra.	209,586	16.53%	2.1	4.9	214	35	621	154	467
Wheat ir.	57,540	4.54%	4.4	6.6	210	35	1,155	264	891
Barley ra.	339,275	26.75%	2.5	5.8	186	35	669	176	493
Barley ir.	77,801	6.13%	4.1	6.2	184	35	970	249	721
Maize ir.	71,043	5.60%	11.9		184		2,190	746	1,444
Alfalfa ir	73,154	5.77%	15.4		107		1,648	190	1,458
Almond ra.	59,022	4.65%	0.6		730		641	85	556
Vineyard ra.	29,064	2.29%	3.8		360		1,368	366	1,002
Olives ra.	35,797	2.82%	1.0		336		336	67	269
Other crops	315,961	24.91%							
Total	1,268,243	100%							

Notes: ra. means rainfed; ir. means irrigated; Data for calculation are derived from the national database (MAGRAMA 2011a, 2011b) and straw values are derived from Moragues et al. 2006; Urbano 2002; Francia et al., 2006; Pordesimo et al. 2004

Costs and cost effectiveness

Table A4.3. Private cost assumptions and yield effect of implementing the mitigation measures by crop type in Aragón

Measure Crop	Private costs (€/ha)	Private benefits (€/ha)	Yield effect (%)
1. Cover crops	Seeds + annualized cost for a pneumatic seed-drill for woody crops (MAGRAMA 2008; Steenwerth and Belina 2008; Gómez et al. 2011)	N purchase costs reduced by 23% in cereals	Yield increase for maize and unaffected for woody crops
Maize ir.	31 (vetch); 42 (barley)	68.7	1.11% (vetch); 1.06% (barley) (Gabriel and Quemada 2011)
Almond ra.	58.4	0	0
Vineyard ra.	53.9	0	0
Olives ra.	57.4	0	0
2. Minimum tillage	Annualized cost for a direct seed drill (MAGRAMA 2008)	Avoided costs of moldboard plow (MAGRAMA 2008)	Yield increase
Barley ra.	73.4	84.7	1.55% (Morell et al. 2011)
Barley ir.	73.4	84.7	1.55% (Morell et al. 2011)
3. Residue management	Loss of straw value for incorporation into soil	Not benefit accounted	Yield unaffected
Wheat ra.	171.5	0	0
Wheat ir.	231.0	0	0
Barley ra.	204.2	0	0
Barley ir.	215.3	0	0
4. Manure fertilization	Operational cost of manure transport (max 3km) and applying (LIFE ES-WAMAR 2010)	Mineral fertilizer cost avoided for barley and N purchase costs reduced by 60% for maize (Meijide et al. 2007)	Yield unaffected
Barley ra.	75	114	0
Barley ir.	75	88	0
Maize ir.	82	277	0
5. Optimized fertilization	Annual soil analysis	N purchase costs reduced by 23% for wheat and doses lower than 60kgN/ha for barley (Morell et al. 2011)	Yield increase
Wheat ra.	6	20.2	1.03% (Van Alphen and Stoorvogel 2000)
Wheat ir.	6	20.2	1.03% (Van Alphen and Stoorvogel 2000)
Barley ra.	6	30.8	1.05% (Morell et al. 2011)
6. Crop rotations (legumes)	Not cost accounted	N purchase costs reduced by 50%	Yield increase
Wheat ra.	0	44	1.40%(López-Bellido and López-Bellido 2001)
Barley ra.	0	57	1.35%(Díaz-Ambrona and Mínguez 2001)

Notes: ra. means rainfed; ir. means irrigated; n.a. means not available

Table A4.4. The annual abatement potential and the cost-effectiveness of the mitigation practices for different crops in NE Spain (Aragón region)

Measure Crop	Annual abatement potential (tCO_2e)	Cost-effectiveness (€/tCO_2e ha^{-1} $year^{-1}$)	Cumulative annual abatement (tCO_2e)
1. Cover crop			
Maize irrigated/Vetch cover	29,838	-657.06	-
Maize irrigated/Barley cover	29,838	-396.27	29,838
Almond rainfed	64,924	237.59	94,762
Vineyard rainfed	31,970	48.95	126,732
Olives rainfed	39,377	52.14	166,109
2. Minimum tillage			
Barley rainfed	159,459	-806.59	325,568
Barley irrigated	36,566	-1168.03	362,134
3. Residue management			
Wheat rainfed	35,630	1009.41	397,764
Wheat irrigated	9,782	1358.82	407,546
Barley rainfed	57,677	1206.86	465,223
Barley irrigated	13,226	1257.94	478,449
4. Manure fertilization			
Barley rainfed	72,944	-176.74	551,393
Barley irrigated	16,727	-415.81	568,120
Maize irrigated	15,274	-905.12	583,394
5. Optimized fertilization			
Wheat rainfed	102,697	-66.87	686,091
Wheat irrigated	28,195	-99.78	714,286
Barley rainfed	166,245	-114.01	880,531
6. Crop rotations (legumes)			
Wheat rainfed	176,052	-345.71	1,056,583
Barley rainfed	284,991	-341.02	1,341,574

References included in Annex 4

Díaz-Ambrona CH, Mínguez MI (2001) Cereal-legume rotations in a Mediterranean environment: biomass and yield production. Field Crops Research, 70(2), 139-151

Francia E, Pecchioni N, Nicosia OLD, Paoletta G, Taibi L, Franco V, Odoardi M, Stanca AM, Delogu G (2006) Dual-purpose barley and oat in a Mediterranean environment. Field Crops Research, 99, 158–166

Gabriel JL, Quemada M (2011) Replacing bare fallow with cover crops in a maize cropping system: Yield, N uptake and fertiliser fate. European Journal of Agronomy, 34(3), 133-143

Gómez JA, Llewellyn C, Basch G, Sutton PB, Dyson JS, Jones CA (2011) The effects of cover crops and conventional tillage on soil and runoff loss in vineyards and olive groves in several Mediterranean countries. Soil Use and Management, 27(4), 502-514

LIFE ES-WAMAR (2010) Environmentally-friendly management of swine waste based on innovative technology: a demonstration project set in Aragón (SPAIN) 2006. LIFE06 ENV/E/000044-ES-WAMAR. Available at: www.life-eswamar.eu

López-Bellido RJ, López-Bellido L (2001) Efficiency of nitrogen in wheat under Mediterranean conditions: effect of tillage, crop rotation and N fertilization. Field Crops Research, 71(1), 31-46

MAGRAMA (2008) Cálculo de los costes de operación de cultivos en diferentes zonas agrícolas [Calculation of the operation costs of agricultural crops in different areas]. Ministry of Agriculture, Food and Environment, Madrid, Spain

MAGRAMA (2011a) Análisis de la economía de los sistemas de producción. Resultados técnico-económicos de explotaciones agrícolas de Aragón en 2011 [Economic analysis of farming systems. Technical and economic results for Aragón in 2011]. Ministry of Agriculture, Food and Environment, Madrid, Spain

MAGRAMA (2011b) Encuesta sobre superficie y rendimientos de cultivos. Informe sobre regadíos en España [Spanish Agricultural Census. Report on irrigation in Spain]. Ministry of Agriculture, Food and Environment, Madrid, Spain.

Meijide A, Díez JA, Sánchez-Martín L, López-Fernández S, Vallejo A (2007) Nitrogen oxide emissions from an irrigated maize crop amended with treated pig slurries and composts in a Mediterranean climate. Agriculture, Ecosystems & Environment, 121(4), 383-394

Moragues M, García del Moral LF, Moralejo M, Royo C (2006) Yield formation strategies of durum wheat landraces with distinct pattern of dispersal within the Mediterranean basin. Field Crops Research, 95(2-3), 182–193

Morell FJ, Lampurlanés J, Álvaro-Fuentes J, Cantero-Martínez C (2011) Yield and water use efficiency of barley in a semiarid Mediterranean agroecosystem: Long-term effects of tillage and N fertilization. Soil and Tillage Research, 117, 76-84

Pordesimo LO, Edens WC, Sokhansanj S (2004) Distribution of aboveground biomass in corn stover. Biomass and Bioenergy, 26(4), 337–343

Steenwerth K, Belina KM (2008) Cover crops enhance soil organic matter, carbon dynamics and microbial function in a vineyard agroecosystem. Applied Soil Ecology, 40, 359-369

Urbano P (2002) Fitotecnia. Ingeniería de la producción vegetal. Madrid, Spain, Mundi-Prensa

Van Alphen BJ, Stoorvogel JJ (2000) A methodology for precision nitrogen fertilization in high-input farming systems. Precision Agriculture, 2(4), 319-332

Annex 5. Guidelines for the interviews and Factsheets

SmartSOIL Real Life Case Study (RLCS) farmer interview questions

Objective: To support novel farmer adoption of these agronomic practices with mitigation potential by delivering factsheets adapted to different Spanish farming systems which exemplify the implementation of neighbouring farmers.

Contribution: B. Sánchez designed the Spanish case studies and coordinated the research team. She carried out the interviews and wrote the results.

Introduction

Explain to the farmer that his/her farm has been selected to show-case a particular practice (or set of practices) and that information from the interview will be used to make a RLCS factsheet for other farmers. The information will also be used to estimate cost effectiveness of practices. Show the farmer an example of a factsheet from another project. No data will be published directly from the template, it will be collated to demonstrate cost effectiveness. The farmer will be shown the factsheet draft to ensure he is happy with the text.

Take good quality photos of the farmer/farm, any farm operations and activities relevant to the practice, and any images of impact (e.g. good soil structure). Ask the farmers' permission to use these.

Interview questions: Focus on minimum tillage, cover crops and management of crop inputs

Name: Rafael Alonso Aguilera

Region: Comarca Campo de Tabernas,Almería, Andalucía, Spain

Farm type: Organic mixed farm

Farm size: 650ha

How long have you been farming?

I am the seventh generation farmer in my family, and I have been farming here since 1995. In total the farm is 650ha, but we also help manage the organic farming on other neighbouring farms. The main product is high quality sustainable organic olive oil. On the farm we also have an olive-oil mill, a small oil museum, a restaurant and accommodation. The soil is mainly sandy-loam and due to the hostile climate where the mean precipitation is around 200mm, we struggle with soil erosion and water retention.

Why did you decide to implement the practices?

The farm has always operated under the philosophy that the soil needs to be maintained and improved for the next generation, because we eat from the soil. If my ancestors could do it well, why are we going to change now? The easiest way to learn how to manage your field is to observe how nature is already performing. Especially under extreme conditions, it is better not to work against nature. For instance, here we cultivate crop varieties which are already adapted to our extreme dry and semiarid conditions.

How have you incorporated minimum tillage, cover crops and crop inputs into your rotations?

Reduced tillage is applied all over the farm, as this helps with the soil erosion problems prolific in this region. Cover crops are implemented more spontaneously for seasonal protection. In terms of inputs, we leave the pruning debris from olives on the soil to provide more nutrients, as well as grass cuttings when they are available. The waste from the olive oil mill is mixed with livestock waste (mainly from sheep) and returned to the field as organic manure fertilization to increase the organic content in our soils.

How did you make the change?

Sustainable farm and soil management have always been in our philosophy. We are always thinking about how to provide more nutrients to our soils in sync with the nature, since they are pretty poor. So the practices that we use in the farm are selected by thinking about soil health. We started using the practices, like minimum tillage by testing on smaller, flatter fields. I developed a plan so that I could make these changes without external financial support or subsidy.

What has been the biggest challenge? And how have you overcome it?

The major limiting factor in the region is the water since the area is a desert and the climate is extreme. We use the water from the aquifer, but below the limit, applying deficit irrigation to avoid over-exploitation of the groundwater. To control the water issue, we decided not to increase the size of the farm and have worked with Almeria University on irrigation systems and water performance in soils.

How has the soil benefited from this change?

We record and analyse out soils, and we have seen an increase in soil organic matter and in turn soil fertility. We know this is from the pruning debris, grass and application of composts. Thanks to these practices, the soil water retention is much better, erosion has reduced and the microorganism population is larger. During the years with more precipitation we have observed a large worm population in our soils. Applying no tillage in the olive fields, you can prevent the olive roots breaking and in turn avoid the time and energy wasted in the root recovery.

How have the yields been affected by this change?

We have similar yields to other farms in the area which use conventional management. We have a mean olive yield of about 8t/ha, which is four times higher than the average production volume in Spain. The conventional farms are using about 40% more water and applying inorganic fertilizer, so we have lower costs associated with the same yields. We use less water and save on fertilizer purchasing. Further, we control the pests by natural predators and we do not need to apply treatments. We have also reduced cost by using the livestock (horses) asa natural mower to control the cover crops.

How has the farm business benefited from this change? What are the financial implications of making the change?

You have to manage your farm as a business, whether or not it is organic. We can sell our products in over 20 countries because of their high quality and sustainable production. We can sell our product for 30% more above the market price for medium quality products and from conventional management, so we have an excellent quality-ratio price. Organic farming requires more labour but it can be covered with this extra 30% in price. Any further cost savings are mainly from the reduced needs of inputs.

Where did you get advice and support to make the change?

When we first started, we didn't have as much available information as we do now. We discussed and commented on our progress amongst ourselves and with other farmers. I have worked with the regional administration, advisory services and with some Universities in several projects about soil erosion and water management. It is important to use all scientific work and information, but you have to adapt it somehow to your area.

What advice would you give to others thinking about the change

Many farmers do not implement such practices because the economic information is not completely available. The information has to be via gross margin or price. The economic support has to be addressed to improve the farm management and to be more efficient if you want to implement organic farming. You will need to have a strategy and economic feasibility to afford the initial investment.

Interview questions: Focus on minimum tillage, direct seeding, crop rotation and residue management

Name: Juan Ramón Alonso García and Carlos Garrachon

Region: Valladolid and Palencia, Castilla-León, Spain

Farm type: Arable

Farm size: 150-200 ha each

How long have you been farming?

Juan Ramón: I have been farming for 14 years. I farm about 200ha of land, which I manage and undertake all the work on.

Carlos: I have been farming for 25 years, but only for the last 14 years have I implemented conservation agriculture on my farm. I also farm around 200ha of land, but hire in contractors to undertake the operations.

Why did you decide to implement the practice(s)?

Juan Ramón: We both implemented the practices about 14 years ago. We both belong to the Association of Conservation Agriculture of Valladolid (AVAC), so part of it was personal conviction. However, we both want to be cutting-edge farmers and reduce our costs.

Carlos: We have the Mediterranean weather influences here with irregular precipitation which makes water a limiting factor. The practices help with this along with improving soil structure and workability.

How have you incorporated minimum tillage, direct seeding and residue management into your rotations?

Carlos: We usually rotate crops including about 50% cereal – 25% legume - 25%oleaginous. For example, 100 ha with 50 ha of wheat or barley and 50 ha of vetch and sunflower or alfalfa. We mainly apply no tillage. However we need to use the decompactor every 5 to 8 years, especially when we are going to cultivate sunflower as the clay soils can become tight which can make root system development more difficult.

How do you make the change?

Juan Ramón: To start with I adopted the practices in only a few fields, as I wanted to test the effectiveness of each practice. After about two years I adopted the practices across the whole farm.

Carlos: I started implementing the management practices on most, if not all, of the farm from the beginning. I felt quite confident as I went to a farmer training in Andalusia promoted by the Spanish Association of Conservation Agriculture (AEACSV).

What has been the biggest challenge? And how have you overcome it?

Carlos: At the beginning the main barrier was the distrust about the effectiveness of this management and the change of mentality. It is something unknown for you and you have to take responsibilities. The new machinery is also a barrier. You have to learn how to use and calibrate the new machinery for direct seeding. The machinery is expensive and is not adapted to local conditions (e.g. different types of soil) and I had to make some modifications to it. When you start to implement these practices, you have many doubts, but after the first production year your confidence is multiplied several times by comparing the results achieved with surrounding conventional farms.

How has the soil benefited from this change?

Carlos: These practices provide enrichment and increase of the soil organic matter and enhancement of soil texture and structure, more workability, less erosion, decrease of run-off and leaching and more worms which make a micro natural tillage into the soil. These practices also correct soil physical properties by, for example, reducing pH of our alkaline soils and then releasing phosphate and potash which can have a beneficial fertilising effect to the soil.

How have the yields been affected by this change?

Juan Ramón: The yield is usually equal to surrounding farms in conventional management but higher than them during water scarcity periods. This is due to the residues which improve soil water retention and reduce the evapotranspiration and thus provides higher availability to the crop.

How has the farm business benefited from this change? What are the financial implications of making the change?

Juan Ramón: The impact of the practices is most noticeable in the net margin (increases about 30%) and in the short term (about 3 years), especially fuel reductions from the first year (cost reductions of about 50%) and fertilisers cost reductions. From the fifth year, your production is clearly increased and the costs are reduced. The cost from machinery is also reduced since the machines work fewer hours than in conventional tillage, the life span of the equipment is longer and there are fewer breakdowns and reduced needs for tractoroil. We also had worse years in the past due to fungal diseases and weeds but they were overcome.

Where did you get advice and support to make the change?

Carlos: We got support and information from the AVAC, from literature about these practices in other regions, websites and other farmers and friends, who had specific information and proven positive results.

What advice would you give to others thinking about the change?

Juan Ramón: To begin with try the practices in just a few fields, and compare the results to conventional agriculture.

Carlos: You need to be patient since positive results can take a few years to emerge. You also need to be as informed as you can.

Factsheet focus on minimum tillage, cover crops and management of crop inputs

SmartSOIL

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 289694.

FOCUS ON MINIMUM TILLAGE, COVER CROPS AND MANAGEMENT OF CROP INPUTS

Name	**Rafael Alonso Aguilera**
Region	**Comarca Campo de Tabernas, Almería, Andalucía, Spain**
Farm type	**Organic mixed farm**
Farm size	**650ha**

How long have you been farming?

I am the seventh generation farmer in my family, and I have been farming here since 1995. In total the farm is 650ha, but we also help manage the organic farming on other neighbouring farms. The main product is high quality sustainable organic olive oil. On the farm we also have an olive-oil mill, a small oil museum, a restaurant and accommodation. The soil is mainly sandy-loam and due to the hostile climate where the mean precipitation is around 200mm, we struggle with soil erosion and water retention.

Why did you decide to implement the practice(s)?

The farm has always operated under the philosophy that the soil needs to be maintained and improved for the next generation, because we eat from the soil. If my ancestors could do it well, why are we going to change now? The easiest way to learn how to manage your field is to observe how nature is already performing. Especially under extreme conditions, it is better not to work against nature. For instance, here we cultivate crop varieties which are already adapted to our extreme dry and semiarid conditions.

How have you incorporated minimum tillage, cover crops and crop inputs into your rotations?

Reduced tillage is applied all over the farm, as this helps with the soil erosion problems prolific in this region. Cover crops are implemented more spontaneously for seasonal protection. In terms of inputs, we leave the pruning debris from olives on the soil to provide more nutrients, as well as grass cuttings when they are available. The waste from the olive oil mill is mixed with livestock waste (mainly from sheep) and returned to the field as organic manure fertilization to increase the organic content in our soils.

How did you make the change?

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FOCUS ON MINIMUM TILLAGE, COVER CROPS AND MANAGEMENT OF CROP INPUTS

What has been the biggest challenge? And how have you overcome it?

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How has the soil benefited from this change?

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For further information please see:
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Factsheet focus on minimum tillage, direct seeding, crop rotation and residue management

SmartSOIL

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 289694.

FOCUS ON MINIMUM TILLAGE, DIRECT SEEDING, CROP ROTATION AND RESIDUE MANAGEMENT

Name	**Juan Ramón Alonso García and Carlos Garrachon**
Region	**Valladolid and Palencia, Castilla-León, Spain**
Farm type	**Arable**
Farm size	**150–200 ha each**

How long have you been farming?

Juan Ramón: I have been farming for 14 years. I farm about 200ha of land, which I manage and undertake all the work on.

Carlos: I have been farming for 25 years, but only for the last 14 years have I implemented conservation agriculture on my farm. I also farm around 200ha of land, but hire in contractors to undertake the operations.

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