



Policy Incentives for Climate Change Mitigation Agricultural Techniques

Project n° 044148
 Project acronym: PICCMAT
 Instrument: Specific Support Action
 Thematic Priority: 8.1 Policy Oriented research / Scientific Support to Policies
 Call FP6-2005-SSP-5A

Deliverable 10: Adaptation and Mitigation

Submission date: September 2008

Start date of project: 1 January 2007
 Duration: 24 months
 Organisation name of lead contractor for this deliverable: ABDN
 Revision: Final

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Contract n° 044148	Authors: J. Olesen, Aarhus University JR Porter, University of Copenhagen	Date: 18.09.2009
PICCMAT	D12: Adaptation and Mitigation	Page 1 / 14

Contract n° 044148	Authors: J. Olesen, Aarhus University JR Porter, University of Copenhagen	Date: 18.09.2009
PICCMAT	D12: Adaptation and Mitigation	Page 2 / 14

Introduction

Impact and mitigation of and adaptation to global warming are the three elements whose sum defines the total costs of climate change. The balance between these costs will alter with greenhouse gas stabilisation (GHG) level. Low GHG stabilisation levels clearly mean lower damage costs, but mitigation is consequently expensive. Mitigation costs may be higher than adaptation until high stabilisation levels. Total costs may change little for stabilisations from current until twice pre-industrial CO₂ levels, and thereafter fall as mitigation costs fall but impact costs rise. Adaptation costs are more uncertain and are difficult to evaluate. The need and rationale for including adaptation is that mitigation actions have decadal to centurial time-lags in their effectiveness with the consequence that adaptation is required to deal with the intervening period.

It is thus important to explore the interactions and tradeoffs between the three elements, for example that mitigation actions may have consequences for adaptation and *vice versa*. Also, synergies may exist such that the same action can have mitigation and adaptation effects and this may be especially the case in agriculture and thus relevant for the PICCMAT project. IPCC 2007 reported that the study of the interactions between mitigation and adaptation is a new area with a small but growing literature and interest from the science and policy community.

Mitigation and adaptation may occur simultaneously, but differ in their temporal and spatial distribution (Smith et al., 2007). Mitigation actions must be taken in the short-term, but can only be expected to have very long-term effects and at a global scale. On the other hand most adaptation options in agriculture have short-term effects, and some also influence the agroecosystem at longer time scales. However, all adaptation options are location specific to take account of local effects on soils and crops. These differences in scales must be considered when evaluating synergies and tradeoffs from adaptation and mitigation.

In this report we start with a general model of the three separate costs as a function of GHG stabilisation level. The idea with the model is to get an initial feel for the GHG stabilisation level at which the three costs may cross over each other. This we do via the modelling the fate and effect of a pulse of CO₂ into the atmosphere and thereafter modelling and comparing how global warming (GW) costs, consisting of damage plus mitigation plus adaptation (i.e. total costs), may differ over CO₂ stabilisation targets between 350 and 750 ppmv. Damage costs of CO₂ emissions and global warming are costs from GW without mitigation actions to reduce and/or adaptation to offset potential damages. The socially optimal mix of costs is likely to alter with stabilisation target.

After the general introduction, we examine the particular case of agriculture in the EU. Based on the mitigation options identified in the PICCMAT project we identify adaptation options that follow from the identified PICCMAT mitigation options and place them in a matrix such that adaptation measures and indicative costs and benefits can be seen. An important and novel issue is the fact that PICCMAT adaptation options pay particular attention to soil quality and soil conservation issues. This approach is in contrast to other adaptation analyses (ie. IPCC 2007), which largely identify development of new varieties and changed crop management as adaptive responses of agriculture to climate change. We argue that adaptive responses that take their starting point in maintaining soil quality can have important adaptive as well as mitigative effects. Agriculture may thus be a sector in which high synergies between adaptation and mitigation could be expected.

Contract n° 044148	Authors: J. Olesen, Aarhus University JR Porter, University of Copenhagen	Date: 18.09.2009
PICCMAT	D12: Adaptation and Mitigation	Page 3 / 14

Modelling of adaptation and mitigation costs

We distinguish three marginal GW costs: unmitigated and un-adapted damage (MDC), damage reduction by prior adaptive preparation (MAC) and mitigation efforts (MMC). Our method is, first, to calculate the long-term damage cost of elevated levels of CO₂ via subsequent radiative forcing and temperature rise. Thereafter, mitigation costs arise from actively reducing the CO₂ level. Adaptation costs are then calculated from temporally offsetting re-discounted damage costs, with the logic that for adaptation to be effective it has to occur in advance of the damage. The three marginal GW costs are: unmitigated and un-adapted damage (MDC), damage reduction by prior adaptive preparation (MAC) and mitigation efforts (MMC). Total damage costs $D(t)$ depend on the stabilised CO₂ concentration ($C(t)$) and the MDC is:

$$MDC = \int_0^T \frac{\partial D[C(t)]}{\partial C} G(t) dt \quad (1)$$

$G(t)$ is the survival of the CO₂ pulse. The equilibrium climate thermal response is scaled to radiative forcing to describe how damage changes with CO₂ level (Equation 2). The radiative forcing (W ($J s^{-1}$) m^{-2}) relative to the pre-industrial atmosphere is given as $[6.3 \cdot \log[C(t)/278 \text{ ppmv}]$ (Shine et al., 1994) with a climate system sensitivity, K_0 , of $0.568 \text{ KJ}^{-1} \text{sm}^2$. Scaling damage values with temperature relative to an equilibrium damage estimate ignores climate system lags that mean that atmospheric warming is not instantaneous. Therefore, we advanced the present-value function, $V(t)$ (3), by 30 years, implying calculation of the MDC of a historic CO₂ profile. This implies that MDCs in Equation 1 are higher than if a non-lagged value function had been chosen, but are valued slightly less.

$$\frac{\partial D}{\partial C} = \frac{K_0}{\ln^\epsilon(2)} \cdot [0.1 + 0.9 \omega(t)] \cdot \epsilon \left[\ln \left(\frac{C(t)}{C_0} \right) \right]^{\epsilon-1} \cdot \frac{1}{C(t)} \cdot V(t) \quad (2)$$

The climatic thermal response has a damage exponential (ϵ) of 1.3 because damage relative to a pre-industrial value (C_0) is likely to rise non-linearly with temperature (Cline, 1992). The present value function ($V(t)$) in equation 3 is based on an increase in p_0 , the initial average per capita income, which reaches a final average per capita income, p_x , with a relative growth rate of a_p :

$$V(t) = e^{-\rho \cdot t} \cdot \left[\frac{p_0 + (p_x - p_0) \cdot e^{-a_p \cdot t}}{p_x} \right] \quad (3)$$

Per-capita income attains a value of p_x/p_0 relative to the present-day. We chose a value of 3, which is conservative compared to the p_x/p_0 ratio of the present day to that 200 years ago in the USA (Cline, 1992). The overall discount rate (ρ) is set to zero since we are looking at the long-term sustainability of social systems. a_p is set to give a 3% p.a. discount rate in accord with personal consumption preferences over a period of several decades (Henderson and Bateman, 1995). Present purchasing parity corrected per capita income $\omega(t)$ in equation (2)

Contract n° 044148	Authors: J. Olesen, Aarhus University JR Porter, University of Copenhagen	Date: 18.09.2009
PICCMAT	D12: Adaptation and Mitigation	Page 4 / 14

increases from 0.13 to 0.6 to reflect larger economic growth rates in developing countries.

The marginal mitigation cost (MMC) of a CO₂ pulse is calculated as the difference between an integration of the yearly damages with this pulse and without it. For adaptation, we assume that humanity can invest in defensive prevention to neutralise future damage. The present value of a future prevented damage at time t , is then its discounted value for time $t+\Delta$; ie. $D(t+\Delta) \cdot V(\Delta)$. We choose $\Delta = 30$, as public projects typically cover that time span. We calculate MACs by re-discounting MDCs with the present value $V(\Delta)$. A society can also react adaptively to GW and incur adaptive costs. In this case (which we do not consider) and given that it is possible to neutralise damages by reactive adaptation, these costs would equal the current MDC.

We find only slight differences in the total costs of CO₂ emissions along stabilisation targets from 370 ppmv to about 600 ppmv (Fig. 1). Thereafter, total costs decline as mitigation costs fall with higher stabilisation levels.

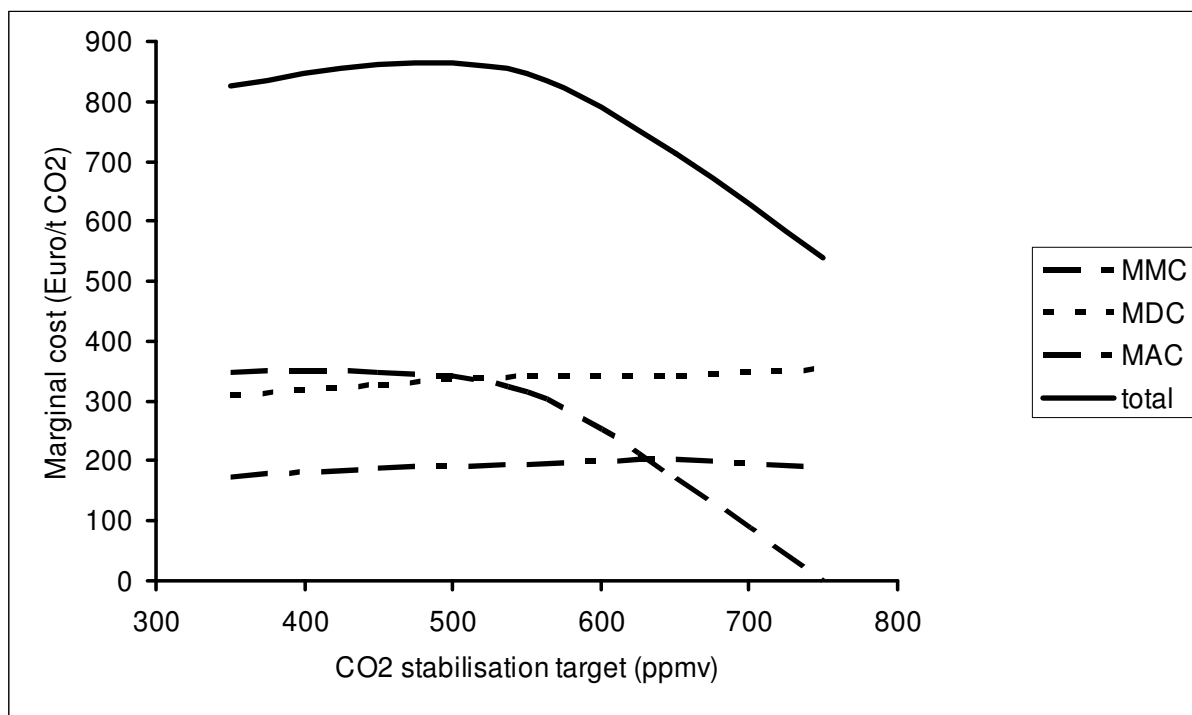


Figure 1. CO₂ total, marginal damage (MDC), mitigation (MMC) and adaptation (MAC) costs for a range of CO₂ stabilisation levels.

The MDC and MAC curves parallel each other with adaptation costs lower than damage costs. MDCs do not increase much with stabilisation target since the absolute CO₂ concentrations cancel in Equation 2 meaning that damage costs are more a function of the sensitivity of climate warming to CO₂ concentration rather than an absolute level. MMCs are high for low stabilisation targets but decline after about 550 ppmv. MMCs become lower than damage costs only after about 550 ppmv and both are higher than adaptation costs at this point. Adaptation costs become larger than mitigation costs at about 650 ppmv, but both are lower than damage costs. Our model suggests that investment in mitigation is the socially optimum solution for levels of CO₂ that are only likely to be seen in the next century and that adaptation gives the lowest marginal costs for CO₂ levels up to twice pre-industrial levels. Also, the value of a tonne of CO₂ depends on whether it is being valued for its damage, mitigation or

Contract n° 044148	Authors: J. Olesen, Aarhus University JR Porter, University of Copenhagen	Date: 18.09.2009
PICCMAT	D12: Adaptation and Mitigation	Page 5 / 14

adaptation possibilities.

Our simple approach to estimate MACs implies perfect foresight, by which it is possible to prevent all damages at time $t+\Delta$ by adaptation at time t . In reality, we cannot prevent all damages by preventative adaptation and post-event adaptation also needs consideration. Perfect preventative adaptation gives the theoretical minimum adaptation costs. We know that total social damage costs are limited to values between our calculated preventative adaptation costs, and a theoretical maximum, which is the total damage.

We identify issues with our model that invites further work. Our underlying damage estimates are uncertain and should only be considered order-of-magnitude estimates. This implies other, probably higher, values of the MDCs, but does not change our fundamental finding that adaptation has a lower cost until high stabilisation levels are met. Also, we have only considered the absolute temperature changes from the enhanced greenhouse forcing and larger climate variability may have a larger influence than simple changes in mean climate (Porter and Semenov, 1999). The influence of GW on population growth has also been exempted from this investigation, which may influence our results. However, our central message is that regional adaptation, for levels of global warming likely to be seen in the next century, is the main and cheapest option to reduce damage from global warming, given the extremely sparse progress in international climate agreements to reduce emissions.

Impacts and adaptation to climate change in agriculture

The greatest challenge of agriculture during the 21st century is probably to feed the increasing number of more and more wealthy people on earth while maintaining soil and water resources (Cassmann et al., 2003). Indeed the projections indicate the growth in population and economy over the next 50 years will require a doubling of food production, including a increase from 2 to >4 billion tons of grain per year, and questions on whether this is achievable has been raised (Gilland, 2002). Climate change significantly adds to this challenge by reducing the quality of soil and availability of water in many regions and by increasing variability of temperature and rainfall (Tubiello et al., 2007). The increasing confidence in climate change projections (Solomon et al., 2007) and the reluctance and slowness in adopting effective mitigation measures to combat climate change put increasing emphasis effective adaptation measures in all parts of society (Parry et al., 2007).

Climate change affect cropping systems through a wide range of direct and indirect pathways (Olesen and Bindi, 2002; Tubiello et al., 2007). The effects may be positive or negative depending on current climate and soils, and depending on the direction of change. It should be stressed that the effects of climate change on crops are mediated through the farmer's management of the genotype x environment interactions, which is crucially dependent on available resources, including climate, soil, water, nutrients and genetic diversity. So far, research on climate change impacts in agriculture has given little emphasis on changes in frequency of extreme events. However, the impacts of increased climate variability on plant production are likely to increase yield losses above those estimated from changes in mean climate only (Porter and Semenov, 2005). This is primarily linked with changes in the frequency of extreme heat waves and changes in rainfall patterns, including more intensive precipitation events and longer drought periods. Changes in climate variability may be particular difficult for many farmers to adapt to, and adaptation strategies to cope with variability may be different than from those dealing with changes in mean climate. Strategies for adapting to increased variability may include measures to avoid periods of high stress or measures that

Contract n° 044148	Authors: J. Olesen, Aarhus University JR Porter, University of Copenhagen	Date: 18.09.2009
PICCMAT	D12: Adaptation and Mitigation	Page 6 / 14

increase resilience of the system by adding diversity in the crop rotation and improving soil and water resources.

Many management-level adaptation options have been proposed and analysed. Most of these are extensions of current practices to cope with climatic variation or adverse environmental conditions (Howden et al., 2007):

- Altering timing and location of cropping activities
- Altering input, such as crops, varieties, fertiliser rates, irrigation etc.
- Use crop genotypes with improved resource use efficiencies, including drought tolerance
- Use of technologies that “harvest” and conserve water and soil moisture
- Manage water to prevent flooding, water logging, erosion and nutrient leaching under increased rainfall
- Improve crop protection practices, including changes in crop sequence in time and space
- Diversifying farm activities, e.g. by integrating crop and livestock production
- Use climate forecasting to reduce production risk

There may be several restrictions to effective implementation of adaptation options, including social, institutional and technical ones (Gregory et al., 2007). Perhaps equally challenging will be the increasing scarcity of water for irrigation and also increasing concern in society for reducing environmental impacts of agriculture and maintaining biodiversity, which will also be affected by climate change.

Several of the adaptation measures listed above may be used to increase resilience to climate change in cropping systems. However, when it relates to soil and water resources, building resilient systems may require long-term planning and changes already now in anticipation of climate change. An example of this is can be illustrated by the link between climate change and soil degradation, which is one of the greatest threats to global food production (Lal et al., 2007). Most of the processes causing soil degradation are enhanced by climate change, being promoted by higher temperatures, more intense rainfall and longer drought periods, which lead to lower soil carbon stocks, increased soil erosion and salinisation (Tubiello et al., 2007). Yet, higher soil carbon contents and better soil structure will be critical for cropping systems to cope with increased climate variability. There is clearly a need within research, advice and policy to focus more on those aspects of agricultural systems that build resilience.

Links between mitigation and adaptation in agriculture

Many of the options available for adapting agricultural activities will influence the emissions of greenhouse gases either by enhancing or reducing the fluxes. However, it should be kept in mind that agricultural activities affect several greenhouse gases simultaneously, and it is the net effect on the global warming potential of all gases that should be considered. There may also be differences between short- and long-term responses to introduction of system and management changes, in particular for measures that involve changes in soil management and input of carbon and nitrogen to the soil. Here we take the starting point the list of mitigation options analysed in the PICCMAT project and evaluate their usefulness from an adaptation point of view. Most of this evaluation is qualitative, since there are very few studies linking adaptation and mitigation in agriculture (Olesen, 2006). Further studies are thus warranted.

Contract n° 044148	Authors: J. Olesen, Aarhus University JR Porter, University of Copenhagen	Date: 18.09.2009
PICCMAT	D12: Adaptation and Mitigation	Page 7 / 14

The primary aim of the mitigation options is to reduce emissions of methane or nitrous oxide or to increase soil carbon storage. The mitigation options therefore all in some way affect the carbon and/or nitrogen cycle of the agroecosystem. This often does not only affect the greenhouse gas emissions, but also the soil properties and the nutrient cycling.

One of the main challenges under climate change is related to the intensification of the hydrological cycle leading to more intensive rainfall and longer dry periods. The result is more rainy conditions and higher risk of soil erosion and nutrient leaching in currently wet temperate climates (Andersen et al., 2006), where rainfall in general will increase in the wet part of the season. Such measures will influence C and N cycling and thus emissions of CO₂, CH₄ and N₂O. In currently dry climate, rainfall may very well be reduced leading to more frequent droughts and higher dependency of stored soil moisture for supporting crop growth and yield. This puts a higher dependency on soil moisture storage and conservation, e.g. through conservation agriculture (Dumanski et al., 2006). This will influence soil carbon storage and possibly N₂O emissions.

Climate change projections show an increase in occurrence of extreme high temperature events and of increase in inter-season variability in temperature and rainfall (Christensen et al., 2007). Adaptation to increased variability will involve increasing the resilience of the production systems (Thomas, 2008). This may be done by improving soil water holding capacities through adding crop residues and manure to arable soils or by adding diversity to the crop rotations (Mäder et al., 2002), e.g. by increasing better alternating crops and adding legumes to cereal based systems. The effects of extremely high temperatures on some crops may be reduced through modifying the microclimate, e.g. by adding shade and shelter as in agroforestry systems (Cannell et al., 1996).

Some mitigation measures may also have negative effects in relation to adaptation. Examples could be catch crops that besides reducing nutrient leakages and adding carbon to soils, also consume water. In situations of water scarcity this water consumption of the catch crop may reduce available soil water for the cash crops and thus negatively affect yields. Other examples of negative effects are establishment of soil covers from crop residues or permanent understories in orchards that act as insulating materials for heat transfer to and from the soil. This insulation will increase the risk of low temperatures (frost) for the crops during night and of extremely high temperatures during daytime.

In summary, the main categories of adaptation options for climate change affecting the mitigation options considered here include:

- Measures that reduce soil erosion
- Measures that reduce leaching of nitrogen and phosphorus
- Measures for conserving soil moisture
- Increasing diversity of crop rotations by choices of species or varieties
- Modification of microclimate to reduce temperature extremes and provide shelter
- Land use change, involving abandonment or extensification of existing agricultural land or cultivation of new land

An estimation of the possible effects of mitigation options selected in PICCMAT on adaptation to climate change is given in Table 1. Many of the mitigation options are estimated to have positive effects on adaptation to climate change, and this largely occurs through increasing the resilience of the agroecosystems to perturbation by climatic variation by increasing the nutrient and water retention in the systems and through prevention of soil degradation, e.g. through erosion (Lal, 2008).

Contract n° 044148	Authors: J. Olesen, Aarhus University JR Porter, University of Copenhagen	Date: 18.09.2009
PICCMAT	D12: Adaptation and Mitigation	Page 8 / 14

Catch crops add a temporary vegetative cover to the soil between agricultural crops. The catch crops are subsequently ploughed into the soil as a green manure. These catch or cover crops add carbon to the soils (Freibauer et al., 2004), but also contribute positively to adaptation by reducing nitrate leaching of arable cropping systems under warmer and wetter winters in Northern Europe (Olesen et al., 2004). Catch crops add a soil cover that significantly reduces risk of soil erosion during high precipitation events (Robinson et al., 1996). However, such crops increase evapotranspiration that may critically reduce soil water storage, if timing of incorporation is not well timed.

Reduced or zero-tillage implies a reduction in soil disturbance, often associated with a higher proportion of crop residues being retained on the soil surface (Holland, 2004). This practice generally increases soil carbon retention (Ogle et al., 2005) and thereby also improves soil water holding capacity. The higher proportion of crop residues on the soil surface reduces soil evaporation and also adds to soil water retention (Pala et al., 2000), and it also protects against soil water erosion (Deizman et al., 1989).

Residue management together with reduced tillage intensity is a part of conservation agriculture, which aims at improving soil function to improve yields and provide resilience against droughts (Dumanski et al., 2006). The application of this technique may be limited in dryland areas, where the amount of crop residues is limited. However, it has been shown that even small amounts of crop residues can reduce wind erosion and contribute to improved soil water storage (Stewart and Koochafkan, 2004), which will be of critical importance to adaptation in dry areas. It also contributes to reducing water erosion of soils (Smets et al., 2008).

Extensification involves the temporary or permanent abandonment of land for intensive agricultural use. This may be through set-aside schemes to lower total agricultural production. Under climate change some currently cultivated agricultural areas may become either too wet or too dry for continued intensive agricultural use and therefore non-viable for agricultural production from an economically point of view (Olesen and Bindi, 2002). Extensification will generally contribute to increased carbon storage in the system (Smith et al., 2000).

Changes in crop productivity and timing of crop production will necessitate changes in fertiliser management (Howden et al., 2007). Adoption of better targeted fertiliser rates and split application strategies will probably need to be part of a strategy for adaptation to a more variable climate for ensuring high nutrient use efficiencies. Such strategies will also tend to reduce nitrous oxide emissions by avoiding high soil nitrate concentrations. The use of nitrification inhibitors may be particularly effective in reducing nitrous oxide emissions from applied fertilisers (Weiske et al., 2001). Such nitrification inhibitors may also have advantages for improving soil nitrogen retention in a climate with more variable rainfall.

The use of more diverse crop rotations that also include forage crops, intercrops and cover crops have often been found to improve soil structure and soil carbon storage (Hutchinson et al., 2007). Such rotations will also be more resilient to climate change by adding diversity to the cropping system, and when properly managed by generally reducing risks of soil erosion and soil nutrient losses.

Adding legumes to cereal based rotations reduces the need for fertiliser N application and adds soil fertility (Nemecek et al., 2008). Legumes also add diversity to the crop rotations thus increasing resilience to environmental change (Thomas, 2008). However, legumes in crop rotations should be seen as a long-term adaptation to increased climatic variability, in

Contract n° 044148	Authors: J. Olesen, Aarhus University JR Porter, University of Copenhagen	Date: 18.09.2009
PICCMAT	D12: Adaptation and Mitigation	Page 9 / 14

particular in dryland systems, where the legumes improve soil structure and soil water holding capacity (Stewart and Koohafkan, 2004).

Permanent or perennial crops represent a system that increases soil carbon stocks compared to annual crops. These crops will form a permanent soil cover that effectively reduced soil erosion and nutrient leaching. Some intercropping systems with perennial legume crops and annual cereal crops have been proposed. However, the competition between the permanent crop and the annual cereal for water and nutrients generally reduces the cereal yields obtained (Thorsted et al., 2006). Such intercropping systems may therefore be even less viable under conditions of increased drought.

Agroforestry involves growing crops and trees together. The trees may be individual trees, shelterbelts, hedgerow or alley cropping. These landscape elements will add shade and shelter with subsequent effects on the microclimate (Cleugh, 1998). This may be used as a strategy to reduce both high and low temperature extremes (Lin, 2007). In addition agroforestry will contribute to reducing soil erosion and nutrient losses, which also have positive effects for adaptation to climate change.

Growing grass in orchards or vineyards adds seasonal protection and soil improvement, which contributes to increasing soil fertility and reducing soil erosion and nutrient leaching. The grass is usually ploughed under or desiccated to accommodate the primary crop being produced on the site. Otherwise the grass crop will compete with the trees for nutrients and water.

For grasslands there are several ways of optimizing management (e.g. adjusting grazing intensity and length and timing of the grazing period). These strategies seek to avoid overgrazing or grazing at times of the year that lead to grassland degradation and to loss of productivity. Better grassland management will therefore reduce soil erosion and improve soil water retention and use.

Grassland renovation can be a response to overgrazing or mismanagement that has led to degraded grasslands. The grasslands may be renovated by seeding a mixture of grasses and legumes that can have positive effects for productivity. Such species mixtures also add resilience to the system that may be particularly beneficial under climate change (Duchworth et al., 2000).

Manure management systems have little relevance as adaptive responses to climate change, since similar manure handling systems are use over wide range of climatic zones (Menzi, 2002). However, application of manure to arable land rather than to grassland has the advantage of improving soil structure for arable cropping systems leading to better soil water holding capacity and thus to improved resilience of these systems to drought.

Many areas of organic soils in Europe currently used for agriculture are drained and have artificially reduced water tables. This contributes significantly to the carbon loss and greenhouse gas emissions from these soils. In northern Europe some of these soils, in particular in riparian areas will be subject to increased winter season rainfall that will put further stress on existing drainage systems. For some of these organic soils or peatlands the only viable options may be renewing drainage systems or abandoning the land for agricultural use. The latter option has the advantage of significantly reducing greenhouse gas emissions.

Contract n° 044148	Authors: J. Olesen, Aarhus University JR Porter, University of Copenhagen	Date: 18.09.2009
PICCMAT	D12: Adaptation and Mitigation	Page 10 / 14

Conclusions

The challenge of adapting agriculture to climate change is not only one of ensuring crop production to maintain food security. It is also a task of maintaining our soil and water resources while at the same time protecting environment and biodiversity. This puts new challenges to agronomic research (Ingram et al. 2008), which in future must consider larger spatial and temporal scales and also work with a range of other scientists to ensure that adaptation strategies are effective not only in terms of crop production, but also environmentally and economically robust, at landscape and regional scales.

The results show that as CO₂ stabilisation targets increase there will be a gradual increase in marginal costs of adaptation that finally will finally exceed the marginal costs of mitigation. However, this analysis assumes that there is no interaction between the mitigation and adaptation measures. The results of the analysis of proposed mitigation measures in agriculture illustrate that this is not the case. In many cases the mitigation options are some of the same options that would need to be introduced for effective adaptation to climate change. This positive interaction will effectively lower the CO₂ stabilisation target where marginal costs of adaptation exceed those of mitigation.

The analysis presented here shows a large potential for synergies between mitigation and adaptation within agriculture. This needs to be incorporated into economic analyses of the mitigation costs. The inter-linkages between mitigation and adaptation are, however, not very well explored and further studies are warranted to better quantify short- and long-term effects on suitability for mitigation and adaptation to climate change.

References

- Andersen, H.E., Kronvang, B., Larsen, S.E., Hoffmann, C.C., Jensen, T.S., Rasmussen, E.K., 2006. Climate-change impacts on hydrology and nutrients in a Danish lowland river basin. *Sci. Total Env.* 365, 223-237.
- Cannell, M.G.R, van Noordwijk, M., Ong, C.K., 1996. The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. *Agroforestry Syst.* 34, 27-31.
- Cassman K.G. et al. 2003. Meeting cereal demand while maintaining natural resources and improving environmental quality. *Annu. Rev. Env. Res.* 28, 315-358.
- Christensen, J.H., Hewitson, B., Busuloc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T., Laprise, R., Rueda Magana, V., Mearns, L., Menendez, C.G., Raisen, J., Rinke, A., Sarr, A., Whetton, P., 2007. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, UK and New York, USA.
- Cleugh, H.A., 1998. Effects of windbreaks on airflow, microclimates and crop yield. *Agroforestry Systems* 41, 55-84.
- Cline, W.R., 1992. *The Economics of Global Warming.* Institute for International Economics, Washington, 1992.
- Deizman, M.M., Mostaghimi, S., Dillaha, T.A., Heatwole, C.D., 1989. Tillage effects on phosphorus losses from sludge-amended soils. *J. Soil Wat. Cons.* 44, 247–251.

Contract n° 044148	Authors: J. Olesen, Aarhus University JR Porter, University of Copenhagen	Date: 18.09.2009
PICCMAT	D12: Adaptation and Mitigation	Page 11 / 14

- Duckworth, J.C., Bunce, R.G.H., Malloch, A.J.C., 2000. Modelling the potential effects of climate change on calcareous grasslands in Atlantic Europe. *J. Biogeography* 27, 347-358.
- Dumanski, J., Peiretti, R., Benites, J.R., McGarry, D., Pieri, C., 2006. The paradigm of conservation agriculture. *Proc. World Assoc. Soil Water Conserv.* P1, 58-64.
- Freibauer, A., Rounsevell, M.D.A., Smith, P., Verhagen, J., 2004. Carbon sequestration in the agricultural soils of Europe. *Geoderma* 122, 1-23.
- Gilland, B., 2002. World population and food supply. *Food Policy* 27, 47-63.
- Gregory P.J., 2005. Climate change and food security. *Phil. Trans. Roy. Soc. London B* 360, 2139-2148.
- Henderson, N., Bateman, I., 1995. Empirical and public choice evidence for hyperbolic social discount rates and the implications for intergenerational discounting. *Env. Res. Econ.* 5, 413.
- Holland, J.M., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. *Agric. Ecosyst. Environ.* 103, 1-25.
- Howden, S.M., Soussana, J.F., Tubiello, F.N., Chhetri, N., Dunlop, M., Meinke, H., 2007. Adapting agriculture to climate change. *Proc. Nat. Acad. Sci.* 104, 19691-19696.
- Hutchinson, J.J., Campbell, C.A., Desjardins, R.L., 2007. Some perspectives on carbon sequestration in agriculture. *Agric. Forest Meteorol.* 142, 288-302
- Ingram J.S.I., Gregory, P.J., Izac, A.M., 2008. The role of agronomic research in climate change and food security policy. *Agric. Ecosyst. Environ.* 126, 4-12.
- Lal, R., 2008. Managing soil water to improve rainfed agriculture in India. *J. Sustain. Agric.* 32, 51-75.
- Lal, R., Follett, F., Stewart, B.A., Kimble, J.M., 2007. Soil carbon sequestration to mitigate climate change and advance food security. *Soil Sci.* 172, 943-956.
- Lin, B.B., 2007. Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee production. *Agric. Forest Meteorol.* 144, 85-94.
- Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P., Niggli, U., 2002. Soil fertility and biodiversity in organic farming. *Science* 296, 1694-1697.
- Menzi, H., 2002. Manure management in Europe: results of a recent survey. In: *Proceedings of the 10th Conference of the FAO/SCORENA Network on Recycling Agricultural, Municipal and Industrial Residues in Agriculture (RAMIRAN)*, pp. 93-102. Strbske Pleso, Slovak Republic, 14-18 May.
- Nemecek, T., von Richthofen, J.S., Dubois, G., Casta, P., Charles, R., Pahl, H., 2008. Environmental impacts of introducing grain legumes into European crop rotations. *Eur. J. Agron.* 28, 380-393.
- Ogle, S.M., Breidt, F.J., Paustian, K., 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochem.* 72, 87-121.
- Olesen, J.E., 2006. Reconciling adaptation and mitigation to climate change in agriculture. In *Boutron, C. (ed.) From regional climate modelling to the exploration of Venus. ERCA - volume 7. Journal de Physique IV France* 139, 403-411.
- Olesen J.E., Bindi, M. 2002. Consequences of climate change for European agricultural productivity, land use and policy. *Eur. J. Agron.* 16, 239-262.
- Olesen, J.E., Rubæk, G., Heidmann, T., Hansen, S., Børgesen, C.D., 2004. Effect of climate change on greenhouse gas emission from arable crop rotations. *Nutr. Cycl. Agroecosyst.* 70, 147-160.
- Pala, M., Harris, H.C., Ryan, J., Makboul, R., Dozom, S., 2000. Tillage systems and stubble management in a Mediterranean-type environment in relation to crop yield and soil moisture. *Exp. Agric.* 36, 223-242.

Contract n° 044148	Authors: J. Olesen, Aarhus University JR Porter, University of Copenhagen	Date: 18.09.2009
PICCMAT	D12: Adaptation and Mitigation	Page 12 / 14

- Parry M.L. 2007. 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, UK.
- Porter, J.R., Semenov, M.A., 1999. Climate variability and crop yields in Europe. *Nature* 400, 724.
- Porter J.R., Semenov M.A. 2005. Crop responses to climatic variation. *Phil. Trans. Roy. Soc. London B* 360, 2021-2035.
- Robinson, C.A., Ghaffarzadeh, M., Cruse, R.M., 1996. Vegetative filter strip effects on sediment concentration in cropland runoff. *J. Soil Water Cons.* 50, 227-230.
- Shine, K.P., Fouquart, Y., Ramaswamy, V., Solomon, S., Srinivasan, J., 1995. Radiative Forcing. In: *Climate Change 1994: Radiative Forcing of Climate Change*, Cambridge, UK: Cambridge University Press, p. 163-203.
- Smets, T., Poesen, J., Knapen, A., 2008. Spatial scale effects of the effectiveness of organic mulches in reducing soil erosion by water. *Earth-Science Reviews* 89, 1-12.
- Smith, P., Powlson, D.S., Smith, J.U., Falloon, P., Coleman, K., 2000. Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. *Global Change Biol.* 6, 525-539.
- Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H.H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, R.J., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., 2007. Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. *Agric. Ecosyst. Environ.* 118, 6-28.
- Stewart, B.A., Koohafkan, P., 2004. Dryland agriculture: long neglected but of worldwide importance. In: Rao, S.C., Ryan, J. (Eds.), *Challenges and Strategies for Dryland Agriculture*. CSSA Special Publication 32. CSSA/ASA, Madison, Wisconsin, USA, pp. 11–23.
- Solomon S. et al. 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
- Thomas, R.J., 2008. Opportunities to reduce the vulnerability of dryland farmers in Central and West Asia and North Africa to climate change. *Agric. Ecosyst. Environ.* 126, 36-45.
- Thorsted, M.D., Olesen, J.E. & Weiner, J., 2006. Width of wheat rows and clover strips influence grain yield in winter wheat/white clover intercropping. *Field Crops Res.* 95, 280-290.
- Tubiello, F.N., Soussana, J.F., Howden, S.M., 2007. Crop and pasture response to climate change. *Proc. Nat. Acad. Sci.* 104, 19686-19690.
- Weiske, A., Benckiser, G., Herbert, T., Ottow, J., 2001. Effect of the new nitrification inhibitor DMPP in comparison to DCD on nitrous oxide (N₂O) emissions and methane (CH₄) oxidation during 3 years of repeated applications in field experiments. *Nutr. Cycl. Agroecosyst.* 60, 57-64.

Contract n° 044148	Authors: J. Olesen, Aarhus University JR Porter, University of Copenhagen	Date: 18.09.2009
PICCMAT	D12: Adaptation and Mitigation	Page 13 / 14

Table 1. Effects of selected mitigation measures on six main groups of adaptation issues. The effects are denoted by + (measure may assist adaptation) or – (measure may contradict adaptation).

Mitigation measure	Soil erosion control	Nutrient loss reduction	Soil water conservation	Genetic diversity	Microclimate modification	Land use change
Catch crops etc	+	+	–			
Reduced tillage	+		+			
Residue management	+		+		–	
Extensification						+
Fertiliser application		+				
Fertiliser type		+				
Rotation species	+	+		+		
Adding legumes	+	+		+		
Permanent crops	+	+	–	+		
Agroforestry	+	+			+	
Grass in orchards & vineyards	+	+	–		–	
Optimising grazing intensity			+			
Length and timing of grazing	+					
Grassland renovation				+		
Optimising storage manure						
Application techniques						
Application to cropland vs grassland			+			
Peatland management						+