

Climate-smart cropping systems for temperate and tropical agriculture: mitigation, adaptation and trade-offs

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Abstract – Climate-smart cropping systems should be designed with three objectives: reducing greenhouse gas (GHG) emissions, adapting to changing and fluctuating climate and environment, and securing food production sustainably. Agriculture can improve the net GHG emissions balance *via* three levers: less N₂O, CH₄ and CO₂ emissions, more carbon storage, and green energy production (agrifuels, biogas). Reducing the application of mineral N fertilizer is the main option for reducing N₂O emissions either directly or by increasing the proportion of legumes in the rotation. The most promising options for mitigating CH₄ emissions in paddy fields are based on mid-season drainage or intermittent irrigation. The second option is storing more carbon in soil and biomass by promoting no-tillage (less fuel, crop residues), sowing cover crops, introducing or maintaining grasslands and promoting agroforestry. Breeding for varieties better adapted to thermal shocks and drought is mainly suggested as long-term adaptation to climate change. Short-term strategies have been identified from current practices to take advantage of more favorable growing conditions or to offset negative impacts: shifting sowing dates, changing species, cultivars and crop rotations, modifying soil management and fertilization, introducing or expanding irrigation. Some crops could also move to more suitable locations. Model-based tools and site-specific technologies should be developed to optimize, support and secure farmer's decisions in a context of uncertainty and hazards. Most of the adaptation and mitigation options are going in the same way but trade-offs will have to be addressed (e.g. increasing the part of legumes will be possible only with significant breeding efforts). This will be a challenge for designing cropping systems in a multifunctional perspective.

Keywords: climate change / adaptation / mitigation / trade-offs / conservation agriculture

Résumé – **Des systèmes de culture climato-intelligents pour les agricultures tempérées et tropicales : atténuation, adaptation et compromis.** Des systèmes de culture climato-intelligents doivent combiner (i) réduction des émissions de gaz à effet de serre (GES), (ii) adaptation au changement et à la variabilité climatique et (iii) sécurisation de la production alimentaire. L'agriculture peut améliorer le bilan des émissions de GES *via* trois leviers : (i) moins d'émissions de N₂O, CH₄ et CO₂, (ii) plus de stockage du carbone, (iii) de la production d'énergie verte (biocarburants, biogaz). Réduire l'application d'engrais minéral ou augmenter la proportion de légumineuses dans la rotation permet de réduire les émissions de N₂O. La réduction des émissions de CH₄ en riziculture inondée impose de revoir la gestion de l'eau (drainage, irrigation). Stocker plus de carbone dans le sol et la biomasse passe par la culture sans labour (moins d'énergie, paillage avec les résidus de récolte), l'utilisation de plantes de couverture, l'introduction ou le maintien de prairies et la pratique de l'agroforesterie. La sélection de variétés mieux adaptées aux chocs thermiques et à la sécheresse est la principale adaptation à long terme au changement climatique. Des stratégies à court terme ont été identifiées à partir des pratiques actuelles, tirant profit de conditions de croissance plus favorables ou compensant les impacts négatifs par le décalage des dates de semis, l'introduction de nouvelles espèces et cultivars, la diversification des rotations, de nouvelles pratiques de gestion du sol et de la fertilisation, l'introduction ou l'expansion de l'irrigation. Certaines cultures pourraient également migrer vers des zones de culture plus appropriées. Des outils basés sur les modèles et l'agriculture de précision devraient être développés afin d'aider les agriculteurs face à un contexte plus incertain et plus

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risqué. La plupart des options d'adaptation et d'atténuation sont compatibles, mais des arbitrages devront être faits : ainsi augmenter la part des légumineuses ne sera possible que si des efforts de sélection importants sont conduits.

Mots clés : changement climatique / adaptation / atténuation / antagonismes / agriculture de conservation

1 Introduction

Climate change, particularly increasing temperatures, altered rainfall patterns, and climate variability (including extreme climate events) will affect dramatically the productivity of crops and their regional distribution in the next decades with severe impacts on food security (Porter *et al.*, 2014). However, despite common trends, regional and local differences are expected.

Sub-Saharan Africa is thought to be the region most vulnerable to these impacts (Challinor *et al.*, 2007). The onset and length of growing seasons governed by rainfall patterns should be deeply modified by 2050 (Sarr, 2012) and crop yields could decrease by 6–24% depending on climate scenario and management strategy (Waha *et al.*, 2013).

In Europe, grain yield stagnation and increased yield variability in cereals have been related to recent changes, and especially to increasing heat stress during grain filling (*e.g.* for wheat, Brisson *et al.*, 2010). Future projected trends include (i) new opportunities due to the northward movement of crop suitability zones and increasing crop productivity in Northern Europe, but (ii) negative impacts in southern parts where climatic risks will intensify while productivity and suitability will decline (Moriondo *et al.*, 2010; Donatelli *et al.*, 2012; Iglesias *et al.*, 2012; Supit *et al.*, 2012). This may be accompanied by a widening of water resource differences between the North and South, and a general increase in extreme rainfall events and droughts (Falloon and Betts, 2010).

Climate change will impact crop production directly or not (Fig. 1). Changes of atmospheric CO₂ concentration, of mean and extreme temperatures, and of rainfall amount and timing will directly affect yields and land use (crop suitability). It will also result in changes in water availability patterns and in additional irrigation requirements that will subsequently affect agricultural productivity (Anwar *et al.*, 2013). In addition, emergent pests and diseases may result in dramatic crop damages (Gregory *et al.*, 2009).

Being partly responsible of the emissions of greenhouse gases (GHG), world agriculture has to reduce its carbon footprint while increasing biomass production to match the needs of a growing population (Smith *et al.*, 2014). In a perspective of climate-smart agriculture (CSA), a variety of innovative crop production systems should be designed and spatially arranged, with three objectives: (i) reducing GHG emissions and storing more carbon in soils and biomass, (ii) coping with changing and fluctuating environments to reduce the vulnerability of agricultural systems, and (iii) securing food production both in quantity, quality and diversity (FAO, 2013; Lipper *et al.*, 2014; Torquebiau, 2015). A wide range of candidate options have been proposed for these multiple goals in relation to public policy, markets, education and training, advisory systems, climate forecasting, plant breeding and cropping systems changes.

Cropping systems are currently defined as the cultural practices applied to crop sequences at field level. More generally the cropping system concept is used when qualifying and managing land use at the territorial level (Boiffin *et al.*, 2014). Cropping systems offer a diversity of options that can be combined to build climate-smart agriculture together with genetics, machinery and information technology. As cropping systems are both levers for adaptation and mitigation and impact food production, multiple trade-offs between cropping systems options have to be identified in a perspective of global optimization of crop production systems (Rosenzweig and Tubiello, 2007).

Numerous studies have reported positive or negative impacts of agriculture on GHG emissions (Pellerin *et al.*, 2013). Until recently, studies addressing the vulnerability of crops to climate change were focusing on climate impact without considering explicitly adaptation. However, the number of papers addressing adaptation has increased exponentially in the last years. According to the *Web of Science*, 75% of the papers mentioning “adaptation + climate change + agriculture or farm or crop” as topics (on a total of 6100) were published since 2011.

In this paper, we present and discuss cropping systems options to reduce GHG emissions and store more C and to contribute to the adaptation of agriculture to climate change (*i.e.* reducing the vulnerability of crop production, increasing resilience and resource-use efficiency). Then we will identify necessary trade-offs to deal with in the context of climate-smart agriculture.

2 Reducing greenhouse gases emissions by modifying cropping systems

The agriculture, forestry and other land use (AFOLU) sector is responsible for 24% (10–12 Pg CO₂ per year) of greenhouse gases emissions worldwide, with concomitant opportunities for mitigation (Smith *et al.*, 2014). A specific feature of agricultural emissions is that they are mostly non energy-related and controlled by biological processes. Agriculture can help improve the net GHG emissions balance *via* three levers: a reduction in N₂O and CH₄ emissions (and also CO₂ emissions due to soil C mineralization and fossil fuel consumption by machinery), additional carbon storage in soils and biomass, and energy production (*e.g.* agrifuels, biogas) to replace fossil energies. Bioenergy production by the agricultural sector poses specific challenges and questions, which have been addressed by many authors (see for instance Gabrielle *et al.*, 2014). In this paper, we will focus on the first two levers for mitigation (Tab. 1).

The current typology for adaptation to climate change and adoption of mitigation measures in the agriculture sector considers (i) incremental changes and autonomous farmer's responses (*e.g.*, shifting the planting date, switching crop varieties, including annual legumes) and (ii) planned and

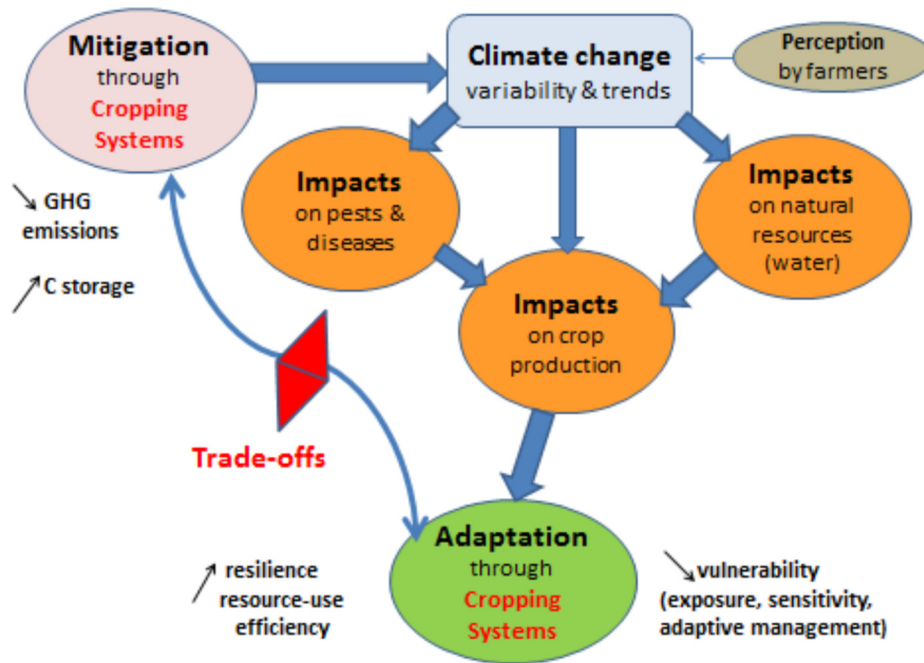


Fig. 1. A schematic representation of the main components of climate change problems and the way cropping systems could influence both adaptation and mitigation.

Fig. 1. Principales composantes du changement climatique en agriculture et voies par lesquelles les systèmes de culture peuvent influencer l'adaptation au changement climatique et l'atténuation des émissions de gaz à effet de serre.

Table 1. Some agricultural practices have been assessed for their performance in reducing nitrous oxides, methane and CO₂ emissions and storing C in soils or biomass ; main options are considered here, in a qualitative way. N₂O can be reduced by more legumes in crop rotations and a better adjustment of N fertilization; C storage can be increased by no-till, residue management, introduction of cover crops, and more trees in agrosystems (from Pellerin *et al.*, 2014).

Tableau 1. Certaines pratiques agricoles ont été évaluées quant à leur capacité à réduire les émissions de protoxyde d'azote (N₂O), de méthane (CH₄) et de gaz carbonique (CO₂) et à stocker du carbone dans les sols et la biomasse ; les principales options sont considérées ici. Les émissions de N₂O peuvent être réduites par une plus forte introduction de légumineuses dans la rotation et par un ajustement de la fertilisation azotée ; le stockage du carbone peut augmenter via le non-travail du sol, la gestion des résidus de culture, l'introduction de cultures intermédiaires, et la plantation d'arbres dans les agrosystèmes (d'après Pellerin *et al.*, 2014).

Levers	Technical options	Expected effect
N fertilization	More legumes in crop rotations Adjust N mineral fertilizer application rates, make better use of organic fertilizer, adjust application dates, use nitrification inhibitors, incorporate fertilizers (to reduce losses)	↘ N ₂ O
Soil tillage	Reduce tillage (direct seeding, occasional tillage, surface tillage)	↘ CO ₂ ↗ C storage
Cover crops and residue management	More cover crops in arable cropping systems, in vineyards and orchards Grass buffer strips	↗ C storage ↘ N ₂ O
Agroforestry and hedges	Agroforestry Hedges around fields	↗ C storage
Paddy rice management	Promote aeration of rice-growing soil to reduce fermentation reactions: reduce the depth of paddy fields, empty them several times per year	↘ CH ₄

transformational changes that require substantial investment (e.g. development of new crop varieties, expanding irrigation infrastructure, introducing agroforestry) (Stokes and Howden, 2010). Autonomous adjustments include farmer's efforts to optimize production without major system changes and without the implication of other sectors (e.g. public policy,

research). Transformational adaptations are those that are adopted at a much larger scale, that are truly new to a particular region or resource system, and that transform places and shift locations (Kates *et al.*, 2012). They refer to major structural changes to overcome adversity caused by climate change. Another distinction is to consider short-term, medium-term

and long-term adaptations, the first one being generally autonomous and the others being more organized and planned by the agricultural sector and policy makers.

2.1 Reduce N₂O and CH₄ emissions from agricultural soils

Nitrous oxide (N₂O) is produced during biochemical denitrification and nitrification reactions occurring in soils or during manure storage. Although many factors control N₂O production and diffusion in soils (aeration, temperature, pH...), annual emissions are highly determined by the amount of N supplied by mineral and organic fertilizers since N₂O production strongly depends on nitrate and ammonium concentrations in soils. In intensively fertilized cropping systems, reducing the application of mineral N fertilizers is the main option for reducing N₂O emissions. This can be achieved without reducing yields by (i) strictly adjusting N fertilizer rates to crop requirements; (ii) taking into account all N sources in the N budget calculation, especially organic products like manures and crop residues whose contribution to N supply is often under-estimated and (iii) improving the efficiency of N supply by splitting fertilizer application in time, and incorporating and localizing fertilizers to avoid losses, especially by ammonia volatilization during spreading, and increase root uptake. Calculating a provisional N budget for an accurate estimation of fertilizers needs remains challenging (Ravier *et al.*, 2016), especially in a context of increasing climatic variability, but N fertilizer supply can be readjusted during crop growth thanks to plant-based diagnostic tools (Lemaire *et al.*, 2008; Ziadi *et al.*, 2010; Gianquinto *et al.*, 2011; Jeuffroy *et al.*, 2013a). Application of nitrification inhibitors is an additional option, but its cost is much higher than the cost of measures based on better adjustment of N fertilization rates (Pellerin *et al.*, 2014). A second lever to reduce N₂O emissions is to increase the proportion of N fixing legumes in crop rotations, either as main crops (including temporary grasslands) or as cover crops between two cash crops. Recent studies have shown that N fixation by legumes is not an N₂O emitting process (Rochette and Janzen, 2005), whereas high concentrations of nitrates and/or ammonium in soils following fertilizer applications are responsible for N₂O emission peaks. Legumes do not require any N application, and their N-rich crop residues can supply N to the following crop. All these measures reducing mineral N application rates, reduce direct N₂O emissions occurring on fields (Jeuffroy *et al.*, 2013b) and indirect emissions occurring downstream after lixiviation of nitrate or volatilization of ammonia. Moreover, they reduce emissions occurring upstream since the manufacture of synthetic nitrogen fertilizers requires large quantities of energy. A better N management in cropping systems is also likely to have positive side-effects on other agri-environmental issues like water quality (less nitrate leaching), air quality (less ammonia volatilization) and preservation of biodiversity (less N deposition on natural ecosystems).

Methane (CH₄) is produced during fermentation of organic matter under anaerobic conditions. Worldwide, 27% of anthropogenic CH₄ emissions are due to enteric fermentation by ruminants, 23% to landfills and waste management, 11% to rice production and 39% to biomass and fossil fuels burning

(Ciais *et al.*, 2013). In well-aerated cropland, soils net CH₄ emissions are usually very low, so that mitigation options in agriculture mainly concern paddy rice cropping systems. The most promising options for mitigating CH₄ emissions in paddy fields without reducing yields are based on water management (Yan *et al.*, 2009; Fumoto *et al.*, 2010). Compared to continuous flooding, mid-season drainage or intermittent irrigation effectively curtail methane emissions (Towprayoon *et al.*, 2005; Khosa *et al.* 2011). Although draining continuously flooded rice fields may lead to an increase in N₂O emission, the global warming potential resulting from this increase is negligible when compared to the reduction in global warming potential that would result from the CH₄ reduction associated with draining the fields (Yan *et al.*, 2009). However, such mitigation practice is only feasible where complete control of water supply and drainage is possible, which is not always the case, especially during rainy seasons. Other mitigation levers are related to the choice of the rice cultivar (varieties with low gas transport capacities and low exudate formation), crop residue management (incorporating organic material in the dry period rather than in flooded periods) and fertilizer management practices (Majumdar, 2003; Xie *et al.*, 2010; Linquist *et al.*, 2012). Since water, carbon and nitrogen dynamics are closely interrelated, the use of process-based biogeochemical models is increasingly needed to explore and assess mitigation strategies for paddy rice cropping systems in the tropics (Chun *et al.*, 2016).

2.2 Increase carbon storage in soils and biomass

Soil carbon stock reflects the long-term equilibrium between carbon inputs (rhizodeposition, crop residues and exogenous organic products) and carbon losses by mineralization. Increasing carbon stocks in soils has been considered as a promising option for mitigating climatic change for decades (Arrouays *et al.*, 2002; Lal, 2011). Increasing C stocks in agricultural soils can be achieved by reducing the C mineralization rate, increasing C input and combining both levers. Reduced tillage has often been considered as a management practice fostering C storage by reducing mineralization rate. Recent meta-analysis of long-term experiments confirmed this trend, although to a lesser extent than initially thought (Angers and Eriksen-Hamel, 2008; Dimassi *et al.*, 2013; Powelson *et al.*, 2014). Additional C storage under reduced tillage is not always observed. It does not occur or is even lowered if biomass production (and therefore C input by crop residues) is also reduced (Virto *et al.*, 2012). The effect of reduced tillage on carbon stocks also depends on climatic conditions, with less additional C storage under wet climate since mineralization of crop residues remaining on soil surface is favored (Dimassi *et al.*, 2014). Moreover, no-till may increase N₂O emissions in poorly-aerated soils (Rochette, 2008), so that all GHG sources should be considered when assessing reduced tillage as a mitigation option (higher C storage in soil if any, less CO₂ emissions by tractors, possible effect on N₂O emissions). Therefore, the identification of soil, climate and agronomical conditions under which reduced tillage can improve the overall GHG budget of cropping systems remains an important challenge for future agronomical research. Increasing C inputs can be achieved by recycling

Table 2. Technical options that could be combined to reduce the vulnerability of cropping systems and take advantage of new cropping opportunities. Different strategies can be applied concerning water and heat stresses: escape, avoidance (*via* crop rationing), tolerance, attenuation, resource conservation, resilience (recovery).

Tableau 2. Options techniques qui pourraient être combinées pour réduire la vulnérabilité des systèmes de culture et tirer parti des opportunités offertes par le changement climatique. Plusieurs stratégies peuvent être mises en œuvre pour faire face aux stress hydriques et thermiques : l'esquive, l'évitement (*via* le rationnement végétatif), la tolérance, l'atténuation, la conservation des ressources, la résilience (récupération).

Levers	Technical options
Crop species & varieties	(stress escape) more appropriate thermal time and vernalization requirements (stress tolerance) increased tolerance to heat shock, drought, waterlogging, low temperature, emergent pests and diseases...
Crop management	(stress avoidance) lower water needs, optimal water use pattern (escape) shifting sowing date to escape water and thermal stresses (avoidance) nutrient applications, planting density and spatial arrangements (<i>e.g.</i> skip row) adjusted to precipitation patterns and yield goals (attenuation) supplementary/deficit irrigation if available (conservation) soil tillage and residue management to maximize soil water storage, reduce evaporation, runoff and erosion
Cropping pattern	Diversify crops and cultivars to increase resilience (rotation, landscape); variety mixtures and intercropping; agroforestry; flexible systems; double and relay cropping
Information and decision system	Use seasonal weather forecasting; model-based decision support systems (DSS)

more organic products (but most of them, especially manure, are already recycled) or by increasing field biomass production and recycling (crop residue incorporation, cover crops between cash crops, cover cropping in vineyards and orchards). Although a large part of the additional biomass is readily mineralized after incorporation in soils, recent studies of long-term experiments have confirmed a positive effect on soil C stocks (Justes *et al.*, 2012; Autret *et al.*, 2016).

Additional C storage in biomass without reducing yields may be obtained by developing agroforestry with a low tree density and planting hedges around fields. These measures also increase soil C stocks by increasing C inputs (leaves, roots). The abatement potential of agroforestry and hedges in temperate and tropical contexts has been highlighted in several studies at national and continental scale (*e.g.* Aertsens *et al.*, 2013 for the European Union). Several technical constraints are likely to limit the applicability of these measures as they cannot be used on small fields that limit machinery use, and cannot be applied to shallow soils or soils with low water holding capacity to avoid water competition with crops. Moreover, additional labor time is required from farmers for tree and hedge maintenance, thus limiting adoption. Even considering these constraints, a national study carried out for France highlighted the high mitigation potential of agroforestry at a moderate cost since additional labor costs are partially offset by economic outlets for additional products like wood (Pellerin *et al.*, 2014).

Most of the previously mentioned management practices promoting C storage in soils and biomass have several positive and a few negative side-effects related to other agri-environmental issues. Weed control may become more complicated with no or reduced tillage, thus increasing the use of herbicides. Using occasional tillage to solve severe weed problems should minimize the negative aspect of continuous no tillage on herbicide use. Besides increasing soil C stocks, cover crops limit N losses by leaching during the intercrop period and may provide N to the next crop, thus reducing N fertilizer needs and N₂O emissions (Justes *et al.*, 2012). They also reduce erosion

risks in susceptible croplands. Antagonisms may appear with water management under dry climate because of water consumption by cover crops, so that interactions between C, N and water cycles should be considered. Besides its mitigation effect, higher carbon content in soils increases soil structural stability, limits erosion risks, increases water infiltration and holding capacity, and improves soil fertility. Trees and hedges in agricultural landscapes provide habitats for wildlife and may help reducing the use of pesticides by favoring biodiversity and biological regulation of pests.

3 Adaptation of cropping systems to changing climate and fluctuating environments

3.1 Short-term risk management at farm level

Adjustments in production technology, crop management and cropping system composition to adapt to climate change at farm level in an autonomous way have been extensively reported in the literature (*e.g.* Smit and Skinner, 2002; Howden *et al.*, 2007; Olesen *et al.*, 2007; Olesen *et al.*, 2011; Anwar *et al.*, 2013). Numerous local and regional studies (field experiments, participatory approaches, modelling exercises) have been conducted to define the best management options to cope with on-going climate variability and future climate scenarios at different time horizons.

We identified a range of short-term strategies based on current practices, either to take advantage of more favorable growing conditions or to offset negative impacts due to the changing duration of growing seasons, and the increased occurrence of droughts and heat waves (Tab. 2).

3.1.1 Shifting planting dates

Shifting planting dates to face new temperature and precipitation patterns is the simplest and low-cost adaptation

strategy. Therefore, it is one of the most reported among climate change studies either in Europe, Asia or Africa (*e.g.* Brisson and Levrault, 2010; Chen *et al.*, 2012; Jalota *et al.*, 2012; Laux *et al.*, 2010; Waha *et al.*, 2013; Waongo *et al.*, 2015). For instance, in Europe, earlier sowing of spring crops (*e.g.* sugar beet, maize) is recommended to take advantage of the longer growing season at higher latitudes. In southern conditions where water stress and high temperatures are expected in summer, anticipating planting and using early-maturing varieties jointly could be an efficient drought escaping strategy for spring-planted crops (Moradi *et al.*, 2013). In the North China Plain for instance, a “double-delay” technology was suggested which consists in delaying both the sowing time of wheat in autumn and the harvesting time of maize, leading to an overall 4–6% increase in total grain yield of the wheat-maize system with climate change (Wang *et al.*, 2012). In the Loess Plateau of China and similar semiarid environments, the wheat sowing date could be delayed by 10 to 20 days in the wet and medium years, and by 20 to 25 days in the dry years compared with the current sowing date (20 September) in order to better adjust the soil water condition to phenological development (Ding *et al.*, 2016). In some Mediterranean regions, it was even suggested to plant sunflower crop in late autumn or winter (instead of spring as usually) to escape water stress at flowering and during grain filling, with good results in water use efficiency and yield (Soriano *et al.*, 2004).

3.1.2 Choosing and including new crops and cultivars

Changing crop species and cultivars to take advantage of opportunities offered by climate change or to minimize the vulnerability to extreme conditions is an additional strategy that should be combined consistently with the change of planting date.

The shorter crop duration with increasing temperature could be compensated for by using long cycle cultivars combined with early sowing dates. This will extend the radiation interception period. Varieties and species with thermal time and vernalization requirements in line with specific characteristics of the growing seasons should be sown preferably.

In the conditions where escaping and avoiding strategies are not applicable, where water resources are scarce and the likelihood of high temperatures increases during the most susceptible phenological phases, varieties and species with increased resistance to heat shocks and drought could be preferred when available. For instance, earlier flowering varieties could be adopted to allow grain filling to occur in the cooler and wetter parts of the year (van Ittersum *et al.*, 2003; Debaeke, 2004). The substitution of irrigated maize by moderately irrigated or rainfed crops (*e.g.* sunflower, sorghum) or fall-planted crops could be recommended to face the increasing water problems in western and southern Europe (Debaeke *et al.*, 2008).

3.1.3 Modifying and widening crop rotations

Crop diversification (at field, farm or territory level) could be widened as a self-insurance measure to cope with more uncertain, infrequent and fluctuant climatic conditions, pest

and disease infestations and price context (Bradshaw *et al.*, 2004). The introduction of additional intra- and inter-specific planned biodiversity at field and farm level and in time (crop rotations) is expected to bring more resilience to the production system under climate variability and change. Running simulations for the second half of the century using the A1B scenario of the IPCC (2007), Nendel *et al.* (2014) designed crop rotations that are expected to become possible in the future in Germany due to a prolonged vegetation period and at the same time shortened cereal growth period: for instance, spring barley succeeding to winter barley could likely be successful but no more (late-sown) winter wheat after sugar beet because of drought exposure. The intensification of the cropping cycle by double cropping could benefit from the longer growing season and allow for larger annual yields in spite of climate change (Graß *et al.*, 2015; Seifert and Lobell, 2015). Very early-maturing varieties could be planted after winter crops which complete their cycle in late spring. However, irrigation may become required for double crop establishment whereas water availability could be restricted in summer in some areas. If climate change also results into impacts on river flows and groundwater resources, the incorporation of double cropping could be constrained by imbalances between water demand and supply. In Sub-Saharan Africa, sequential cropping systems (including double cropping) is also reported as a way to maintain overall crop production, provided farmers adapt the sowing dates to the changing climatic conditions (Waha *et al.*, 2013).

In the next decades, the cropping landscape will be probably partly modified with climate change and some crops and cropping systems will migrate to more suitable locations. In Europe, heat-requiring crops will move towards northern regions (Tuck *et al.*, 2006) with the expansion of climatically suitable areas. This should bring new opportunities for diversifying winter-based crop rotations.

3.1.4 Increasing water availability and water use efficiency by irrigation, crop management and cropping systems

Supplemental or deficit irrigation (either expanded or introduced) is an effective way to maintain or increase grain yield in dry conditions, but future water resources could be limited because of competition among users, especially in the Mediterranean area. Extra precipitation in winter could however be stored for securing summer irrigation when possible. The need for water security will be greatest in Southern Europe as a result of increased production vulnerability, reduced water supply and increased demands for irrigation (Doll, 2002; Brisson and Levrault, 2010; Falloon and Betts, 2010; Zhao *et al.*, 2015). For instance, irrigation is projected to considerably improve and stabilize the yields of late-maturing cereals and of shallow rooting crops (maize and pea) on sandy soils under the continental climate of Germany (Nendel *et al.*, 2014).

It has been often reported that crop management still offers a range of opportunities – that could be optimized – to cope with drought-prone conditions and changing climate in rainfed agriculture, although water conservation strategies will also be necessary in deficit irrigated systems (Debaeke and Aboudrare,

2004). In most cases, but mainly in semi-arid regions, the use efficiency of scarce water resources has been increased by promoting soil and water conservation techniques as mulching in no-till systems for reducing soil runoff and evaporation (Aboudrare *et al.*, 2006). Tillage practices (minimum or no tillage), which include maintaining crop residues from previous harvests on the soil surfaces, are likely to help maintaining soil quality, protecting against erosion, and facilitating water infiltration (Lal *et al.*, 2011). For instance, in Colorado, model simulations showed that up to year 2075, no-tillage should maintain higher wheat yields than conventional tillage in a wheat-fallow rotation (Ko *et al.*, 2012). In Australia, adoption of zero tillage, stubble retention, early sowing, enhanced weed control, and perennial crops and pastures are all suggested to farmers for adapting to reduced precipitation under rainfed conditions (Howden *et al.*, 2007; Stokes and Howden, 2010).

Nitrogen fertilizer management needs to be adjusted to increasing or decreasing yield expectations and to decreasing soil moisture. In soils containing sufficient amounts of moisture and organic matter, enhanced mineralization with increasing temperature must be accounted for (Nendel *et al.*, 2014). However, this may not happen if soil moisture is too low or if droughts are prolonged in time with climate change. The rate and timing of N fertilizer application will be changed as a function of soil moisture in order to maintain the efficacy of plants to use N fertilizer but also to optimize crop canopy development and duration according to available transpirable water (*e.g.* for preventing haying-off in cereals).

Implementation, maintenance and enhancement of agroforestry could contribute to climate change adaptation locally by maximizing the use of soil water resource (Abildtrup *et al.*, 2006; Nguyen *et al.*, 2013).

3.2 Long-term adaptation of the agricultural sector

Given the gradual change of climate in the past, farmers have adapted autonomously by successive technical adjustments to climate change and variability as previously described. However, with the large climate change anticipated by the end of this century, transformational changes (in land allocation and management, farming systems, and plant breeding) could be planned considering possible disruptions in farming systems, land use, and resulting crop productivity (Bindi and Olesen, 2011; Kates *et al.*, 2012; Anwar *et al.*, 2013).

Breeding for new varieties better adapted to thermal shocks (heat and cold), drought, waterlogging and higher atmospheric CO₂ concentration is often suggested as the major long-term adaptation to climate change as current cultivars were selected for long with different targets (Ceccarelli *et al.*, 2010; Boote *et al.*, 2011; Ziska *et al.*, 2012). For instance, sunflower varieties adapted to early planting with increased vigor should be selected to take advantage of autumn or early spring planting dates (Houmanat *et al.*, 2016). However, breeding is often a slow process (about 10 years to develop a new crop cultivar to the point of commercial production), so it must begin well before it is expected that new cultivars will be needed (Asseng and Pannell, 2013). Uncertainty about the extent of future change is very high for rainfall, moderately

high for temperature and relatively low for CO₂ concentration. The impact assessment of adapted cultivars would strongly depend on the assumptions made on breeding advances (Graß *et al.*, 2015). However, given that climatic changes are relatively slow, there is more time for annual field crops to deliver suitable outputs in time. Several public-private research consortia (*e.g.* AMAIZING for maize, SUNRISE for sunflower) are still running in France to identify drought-tolerant materials and accelerate the creation of varieties better adapted to climate change in Europe (Debaeke *et al.*, 2017).

Model-based tools, climate forecasting and site-specific technology should be developed to optimize, support and secure farmer's decisions. Remote sensing (drone, satellite) and precision farming could be used to increase the information on plant canopies and maximize resource-use efficiency. Adaptation could range from tactical fine-tuning to deep changes in the nature of cropping systems with downstream impacts on land use and agricultural sector activity (machinery, inputs, market). The extent of numerical agriculture and the willingness to diversify crops and varieties to increase the resilience at farm or territorial level will change deeply the socio-technical system (*e.g.* cooperatives, consultants, seed companies) with possible lock-ins in the adoption of innovations.

4 Antagonisms, synergies and trade-offs between mitigation and adaptation

In adopting adaptation options (Tab. 2), however, it is necessary to consider the multifunctional role of agriculture and the potential contribution of the agriculture sector in GHG mitigation (Pellerin *et al.*, 2013). According to Smith and Olesen (2010), most categories of adaptation options for climate change should have positive impacts on mitigation by improving nitrogen use efficiencies and soil carbon storage (*e.g.* measures for reducing soil erosion, conserving soil moisture and preventing nutrient losses, adjusting N and water rates to actualized yield goals, diversification of crop rotations...).

For instance, conservation agriculture based on minimum soil disturbance, retention of crop residues, continuous soil covering with vegetation or organic mulch, diversified crop rotation and plurispecific stands is a way to improve carbon sequestration in soils and nutrient cycling, reduce soil degradation, secure food production (especially in smallholders farms in the tropics), and exploit opportunities when offered by longer growing seasons (Brouder and Gomez-Macpherson, 2014; Giller *et al.*, 2015; Craheix *et al.*, 2016). By reducing soil erosion and nutrient leaching, conserving soil moisture, and increasing crop biodiversity, conservation agriculture could be a pillar of climate-smart agriculture in most parts of the world. Over the past 10 years, it has been promoted among smallholder farmers in the tropics, often with disappointing results (Giller *et al.*, 2015). First, conservation agriculture requires more labor for weed control operations (when no chemicals are used) and secondly, the competition for crop residues used for soil mulching or animal feeding is a problem in mixed crop-livestock farms in the tropics.

Similarly, agroforestry is often mentioned as a good solution for maximizing the use of soil resources (water, nitrogen) and modifying microclimate to reduce temperature

extremes and provide shelter, while producing more biomass than single crops and then storing a larger amount of C in the soil-plant system. This is a promising option for smallholder farmers in Africa with well-documented yield and profitability improvements, which seems more conclusive and easier to promote than conservation agriculture (Kaczan *et al.*, 2013).

Low input management in general is recommended to adapt crop canopy development and yield target to decreasing water resources: if properly applied, it should also reduce N₂O emissions as N fertilizer requirement is reduced. Organic agriculture based on the use of legumes and manure as substitutes to mineral N fertilizers contributes to GHG mitigation and to adaptation to climate change: crop diversification is often the rule, soil storage capacities are generally improved in relation with increasing organic matter content and related soil stability, which increases water infiltration rate (Niggli *et al.*, 2009; Lal *et al.*, 2011; Kölling and Elola-Calderón, 2012). However, the debate still exists on the capability of organic and low input agriculture to feed the growing world population. From a meta-dataset of 362 published organic-conventional comparative crop yields, de Ponti *et al.* (2012) reported that crop yields in organic systems were on average 80% of conventional ones.

On the other hand, some mitigation measures may not be as positive for the adaptive capacity of farming systems. The contribution of legumes to reduce GHG emissions and to limit the exhaustion of fossil fuels has been proved to be very important (Jensen *et al.*, 2012; Jeuffroy *et al.*, 2013b; Peyrard *et al.*, 2016). Numerous agronomic and environmental benefits of legumes have been reported (Voisin *et al.*, 2014), their contribution to soil fertility being one of the key factors in sustaining the production of cereal crops in rainfed dry areas in developing countries and more generally in low input systems. In addition, the indeterminate growth pattern of most legumes provides plasticity to environmental stresses by allowing the development of additional flowers and then seeds when more favorable growing conditions occur (Vadez *et al.*, 2012).

However, the restricted root development of most grain legume species may limit water and nutrient uptake, especially at late growth stages when environmental stresses are frequent. Symbiotic N₂ fixation which takes place in the top soil layers is extremely susceptible to drought (Liu *et al.*, 2011). High temperatures may affect dramatically anthesis and seed set contributing to flower abortion (Daryanto *et al.*, 2015). Consequently, the yield of food legumes grown in arid to semi-arid environments are usually variable or low due to severe heat and terminal droughts that characterize these areas. Even in wetter environments, water deficiency may still occur over a period of a few weeks, causing significant yield loss. Therefore, breeding efforts are necessary to improve the adaptation potential of legume crops to heat and water stresses concomitantly with earlier sowing dates, development of winter types, and intercropping with cereals (Cutforth *et al.*, 2007; Vadez *et al.*, 2012).

Sequential multiple cropping (double or relay; main and cover crops) is often advocated as effective method for increasing crop productivity while protecting soil and storing more carbon (Chataway *et al.*, 2011; Rao *et al.*, 2015). In regions where water is limited, more irrigation will be

necessary to make possible the summer growth of double crops or the establishment of cover crops at the end of summer (Meza *et al.*, 2008). In addition, more transpiration and possible soil water shortage are expected when extending the duration of green canopies. In some regions, one-year fallow periods will have to be maintained for storing the critical water volume for crop production in subsequent year as traditionally. However, in the dry Canadian Prairie, this system was found to be prone to wind erosion and other negative side-effects on soil health and it has been replaced with cereal / grain legume rotations (Zentner *et al.*, 2004).

5 Conclusions

Through this short review, we pointed out numerous actionable mitigation and adaptation options and highlighted some trade-offs to deal with when designing multi-functional cropping systems adapted to climate-smart temperate and tropical agriculture. In most cases, adaptation and mitigation measures are not specific of either temperate or tropical agroecosystems although they may differ by their modalities in each environment.

Some adaptations options are more driven by long-term trends: firstly, with increasing temperature, planting dates have been shifted and crop durations modified using current varietal panels, then new crop species will be progressively introduced, and later, innovative varieties will be cultivated issuing from a breeding process integrating explicitly these trends (*e.g.* CO₂, temperature, drought). Besides, diversifying crop plans and rotations and promoting multiple cropping with a range of species and varieties should be rather seen as an adaptive response to the increasing inter-annual and intra-season climatic variability.

Cropping systems based on biodiversity and sustainable soil management (*e.g.* agroforestry, conservation agriculture), and using less (or no) chemical inputs (organic farming) could result in a satisfying compromise between food production, adaptation and mitigation to climate change, thanks to new biological regulations that have emerged in such low-chemicals and diversified cropping systems. Indeed, as stated by Tittonell (2015), “agroecology is climate-smart”. However, during the transition phase to stable agroecological systems, crop production will be probably depressed by climatic factors and uncontrolled input reduction. Therefore, crop breeding will have to propose urgently suitable cultivars for such production systems, not only water and heat resistant cultivars but also more vigorous and multiple disease-resistant ideotypes, which cover rapidly the soil for water conservation and weed suppression.

Establishing climate-smart and resilient cropping systems may involve the implementation of integrated strategies comprised of relevant sets of management practices rather than implementing specific practices one at a time. To achieve this goal, methods for designing and assessing climate-smart cropping systems (based on crop modeling, prototyping and multicriteria approaches) have to be selected and adapted to the new and projected climatic context. When testing the adaptation and mitigation solutions in the real world, farm constraints will have to be considered explicitly and decision-making tools will be required to put in practice such complex strategies at field and farm level.

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