SUNFLOWER CROP AND CLIMATE CHANGE IN EUROPE: VULNERABILITY, ADAPTATION, AND MITIGATION POTENTIAL

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ABSTRACT

Climate change is characterized by higher temperatures and CO_2 concentrations, extreme climatic hazards and less water available for agriculture. Sunflower, a summer crop often cultivated in drought-prone areas, could be more vulnerable to the direct effect of heat stress at anthesis and drought during its growing cycle, both factors resulting in severe yield loss, oil content decrease and fatty acid changes. Some adaptations through breeding, crop management, and cropping systems could be designed and enhanced to cope with these negative impacts. At the same time, new cultivation opportunities could be addressed in some parts of Europe where sunflower is not grown presently. In addition, sunflower crop could participate to the mitigation solution as a low GHG emitter compared to cereals.
Sunflower models should be revised to account for these emerging environmental factors in order to reduce the uncertainties in yield and oil predictions. The future of sunflower in Europe is probably related to its potential adaptation to climate change but also to its competitiveness and attractiveness for food and energy.

Key-Words: climate change, CO2, temperature, crop model, biotic stress, adaptation, mitigation

INTRODUCTION

In Europe, sunflower is mostly cultivated in Southern and Eastern regions. In 2013, Russia, Ukraine (both 49 %, 17.7 Mt) and UE-28 (19 %, 6.8 Mt) were the largest sunflower grain producers in the world accounting for 68 % of global volume. Sunflower crop is covering more than 4.5 M ha in UE-28: Romania, Spain, France, Bulgaria and Hungary being the main contributors (90 % of the UE-28 area). However, in most of these countries, there subsists major yield gaps (national yield between 1.1 and 2.4 $t.ha^{-1}$) and the slope of actual yield progress is rather flat in spite of the steadily genetic improvement (e.g. Salvi and Pouzet, 2010 for France). Climate change could be responsible for yield limitation as was observed for wheat (Brisson et al., 2010) although changes in cultural practices and land use could contribute as well.

The Intergovernmental Panel on Climate Change (IPCC) has predicted that the CO2 concentration may increase by 660–790 ppm from 2060 to 2090 (IPCC, 2007: IPCC 2014). This is expected to raise global temperatures due to the CO2 capacity to absorb infrared light and possibly change the precipitation patterns. In the period 1901-2005, the average annual temperature rose throughout Europe by 0.9 °C (Lotze-Campen, 2011); since the end of the

80s, the elevation of air temperature was clearly observed and the climatologists are speaking of climatic trend and not of interannual variability.

Global Climate Models (GCMs) indicate strongest warming over Eastern and Northern Europe during winter and over Western and Southern Europe during summer (IPCC 2007; 2014). Especially in the Southwestern parts such as France, Spain and Portugal, increase in average summer temperatures may exceed 6 °C by the end of the century. In addition, maximum temperatures could increase much more in Southern and Central Europe than in Northern Europe. However, precipitation trends should vary regionally (Lotze-Campen, 2011). In N. Europe and most of the Atlantic region, mean winter precipitation will increase contrary to the Mediterranean area (especially in the eastern part). Projections of seasonal precipitation patterns vary as well. It is likely that winter precipitation in Western, Northern and Central Europe will increase while it will decrease over the Mediterranean region. Summer precipitation will decrease substantially in Southern and Central Europe and to a smaller degree in Northern Europe. However, during spring and autumn, precipitation change should be marginal. Overall, the intensity of daily precipitation should increase substantially. Heat waves and droughts will occur more often (especially in the Mediterranean and much of Eastern Europe) due to the combined effect of warmer temperatures and less summer precipitation. In addition, droughts will start earlier and last longer.

Therefore, in its traditional production areas, sunflower crop will be exposed to major climate change and potentially impacted by water and temperature stresses. Sunflower is commonly viewed as a drought-tolerant crop and consequently as a possible solution for regions where water resources (used for irrigation) are decreasing and in situations where soil water deficit is expected to increase dramatically. When water is fully available, maize or soybean are preferred, and sunflower is often restricted to marginal areas or unirrigated farms. However if climate change is a threat for sunflower in southern and eastern regions, it could also offer new cropping opportunities in northern parts of Europe. As the only summer oilseed crop in Europe, it could break winter crop rotations where too much fertilizers and pesticides are currently used.

For the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change without adaptation will negatively impact yields for local temperature increases of 2°C or more, although individual locations may benefit (Porter et al., 2014). No such evaluation was produced for sunflower crop in the last IPCC reports. This justified this preliminary review (i) of the impacts of climate change on sunflower grain and oil yields, (ii) of possible adaptation options, and (iii) of the contribution of sunflower to greenhouse gases (GHG) emissions.

CROP SUITABILITY

Sunflower cultivation is currently limited to Southern Europe and parts of Central / Eastern Europe for temperature reasons. A northward shift of the northern limits of crop suitability is likely to occur as temperature steadily raises (Olesen and Bindi, 2002). It is commonly admitted that the area suitable for crop growing may shift northward by 120-150 km per 1°C increase in annual mean temperature. In addition, sunflower could also become viable at higher altitudes than presently. In the Northern regions and in the continental part of Europe, warming will extend the length of the potential growing season allowing earlier planting and harvesting. Drier conditions can also increase the soil workability in spring.

Most of the crop suitability studies are based on thermal requirements (base temperature and growing degree days). Early studies still concluded to a possible migration of the crop northward with global warming (Carter et al., 1991). Tuck et al. (2006) used climate scenarios based on four IPCC SRES emission scenarios (A1FI, A2, B1 and B2) implemented by four GCMs (HadCM3, CSIRO2, PCM and CGCM2) to predict the potential distribution of bioenergy crops in Europe under present and future climate. Their assumptions were that sunflower requires between 350 and 1500 mm of rain per year, with minimum and maximum monthly temperatures of 15 and 39 °C, respectively, between April and September. According to all models, sunflower will continue to be potentially grown in over 60% of southernmost Europe (35–44°N). The four models predicted very different potential distributions in Central Europe by the 2080s due to the different combined predictions of temperature increase, and change in precipitation among them: a 25% increase in 45–54°N by the 2080s due to increased summer temperatures (CGCM2 and HadCM3) vs. a decline of up to 25% in this latitude (CSIRO and PCMA). Sunflower should take advantage of the improved thermal regime (higher summer temperatures) at northern latitudes.

Some studies explicitly considered the extension of sunflower crop to southern England as a possible adaptation to climate change. The projections from UKCIP02 data indicate that the area suitable for sunflower production (using very early cultivars) will increase to approximately 79% of the land area of England by 2050 (Cook, 2009). However, when considering competition with other break crops at farm level, Gibbons and Ramsden (2008) concluded that sunflower area could increase from 0.3% in the baseline through 0.4% in the 2020s to 1.9% in the 2050s which looks quite minor. Hence, while the sunflower area is sensitive to the degree of climate change, there is little evidence of a ‘tipping point’ for a shift in break crops, within the range of climate outcomes modelled.

IMPACTS ON CROP YIELD

At southern latitudes, temperature increases, precipitation decreases as well as increases in climatic interannual variability, and a higher frequency of extreme events are to be expected (IPCC, 2014). These combined changes will lead to a shorter growing season (especially grain filling phase), increased water shortage and heat stress, which will reduce yields, lead to higher yield variability, and probably reduce the agricultural area of this traditional crop in regions as Spain, Portugal, Italy, and SW France.

To document these threats and be more accurate at regional level, several simulation-based studies were recently published where conclusions were given for sunflower. The most complete and recent one (AVEMAC project) was produced by JRC (EU) in 2012 (Donatelli et al., 2012; 2015). Two GCMs were used: Hadley CM3 (warm scenario) and ECHAM5 (cold); yield simulations were performed with the CropSyst model (Stöckle et al., 2003) at 2020 and 2030 horizons with or without technical adaptations. Both potential and water-limited yields were simulated for NUTS2 regions of EU-28. The average [CO2] in the atmosphere has been set to 355 ppm for 2000 (baseline), 400 ppm for 2020 and 420 ppm for 2030, in coherence with IPCC assumptions.

In terms of potential yield, yield improvement was simulated by 2020 compared to baseline time horizon in a magnitude of 5-10% or no change in whole Europe except decline in some places of Portugal, Romania and Bulgaria. Whereas, in 2030 time window, a detrimental effect of climate change by 5-20% was expected in southern parts of Europe (Spain, Italy, Hungary, Romania and Bulgaria) which might be due to the fact that high average "seasonal" temperatures can limit the photosynthetic rates and reduce light interception by accelerating phenological development. In contrary the yield gain in Northern France and Germany suggests that global warming may increase the length of the growing period and render suitable conditions for sunflower growing. From the warm 2030 scenario, a potential decrease in sunflower production of around 10% was simulated for all important Spanish regions. In France, potential decreases are estimated in sunflower production from 4% to 8% depending on the regions. Almost all regions in Hungary, Bulgaria and Romania are estimated to be potentially affected by a significant decrease of 12-14 % in 2030. The analysis for the cold scenario anticipates to 2020 the variations foreseen in the warm scenario in 2030 for all most important Spanish regions. The 2030 cold scenario almost reflects the results obtained with the warm scenario except in France.

Considering water-limited yields (Figure 1), the results show an improvement (with HadCM3) in sunflower yield in Spain, Italy, Romania and Bulgaria (in general areas at southern latitudes) with some patches of decline in France and Germany in 2020, compared to the baseline time horizon. The improvements can be directly linked to the higher precipitation prediction compared to baseline. By 2030 the improvements get milder in Southern European countries, and countries in Eastern Europe see 10–30% yield decline. Higher evapotranspiration coupled with less rainfall compared to baseline period are expected with this scenario.

In conclusion, sunflower yield was simulated to potentially improve at northern latitudes, but with negative effects on yield at southern latitudes. In the warm scenario little to no potential changes are expected for sunflower by 2020; however, by 2030 the analysis indicates potential decreases in production in various areas, if adaptation to climate change is not taken into account.

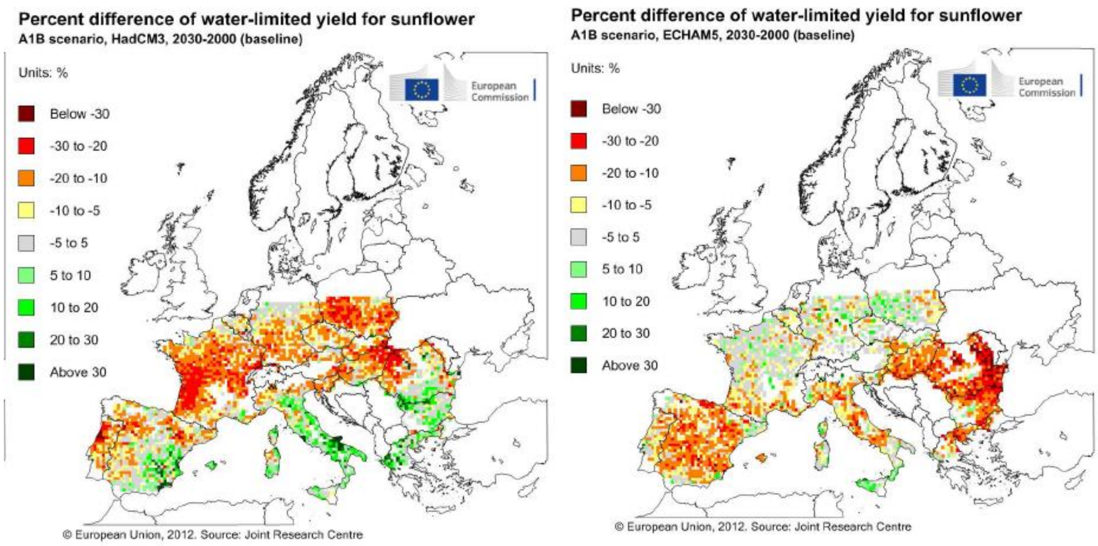

Figure 1 – Change in relative term of simulated water-limited sunflower yield for 2030 using the 'warm' (HadCM3) and the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered (Donatelli et al., 2012)

Since the pioneering study of Harrison and Butterfield (1996), several other studies have simulated the impact of future climate on sunflower yield at local, regional or national levels. Be careful that as crop models, GCMs, RCMs and GGE scenarios differed among studies as time is running, contradictory conclusions were often drawn.

Tubiello et al. (2000) investigated with CropSyst and two GCMs the potential effects of doubling the atmospheric [CO2] from 350 to 700 ppm on sunflower yields at two Italian locations. They concluded to limited changes for unirrigated sunflower as a consequence of soil water refillment during fallow period.

Guilioni et al. (2010) used both SUNFLO and STICS crop models (both including CO2 effects) to simulate baseline, next and far future climate. They concluded to minor changes for 12 locations in France, the positive effects of atmospheric CO2 compensating for negative effects of water stress. However they concluded to an increase of interannual variability during vegetative period. Crop duration will be reduced by 4 to 6 days per °C for flowering time and by 7 to 12 days per °C for harvest date, as a function of RCM and genotype considered. The potential extension of sunflower crop northward in France was thus confirmed. The number of hot days (Tmax > 32 °C) during grain filling could increase from 8 (baseline) to 22 (far future) in Toulouse (SW France).

At European level, Moriondo et al. (2011) assessed the direct impact of extreme climate events (i.e. heat stress at anthesis stage) by using the outputs of HadCM3P regional climate model as drivers of a modified version of CropSyst model. They concluded that the increase in both mean temperatures and temperature extremes for the future period (2071–2100) under A2 and B2 scenarios resulted in: (a) a general advancement of the main phenological stages; (b) shortening of the growing season; (c) an increase in the frequency of heat stress during anthesis with respect to the baseline (1961–1990). The reductions in sunflower yields in the Mediterranean area changed on average from −14% to −34% (A2 and B2 scenarios), and the risk of low yields (i.e. below 1.8 t ha^{-1}*)* increased from 8% to 24%, where the highest differences were observed in the NE and SE regions and in the flat areas. In these regions, sunflower will be more prone to the direct effect of heat stress at anthesis and drought during its growing cycle if no adaptation is introduced.

CROP MODELS FOR EXPLORING THE IMPACTS OF CLIMATE CHANGE

Simple models have been used to map crop suitability based on growing degree days. Traditionally, yield estimation has been based on empirical data, simple evapotranspiration models and, lately, on process-based models (Garcia-Lopez et al., 2014). The impact of climate variability and climate change on grain yield and quality are now exclusively investigated using crop simulation models as recent developments and refinements have been done (formalisms, databases, climatic projections). Crop responses (development, growth and yield) are predicted by combining future climate conditions, obtained from GCMs and RCMs with the simulation of CO2 physiological effects, derived from crop experiments (e.g. FACE, see the review of Ainsworth and Long, 2005).

Crop models currently used for simulating sunflower yield in response to various environments differing by temperature and water are either:

- Generic: STICS (Brisson et al., 2003), CropSyst (Stöckle et al., 2003 ; Moriondo et al., 2011), EPIC/EPIC-Phase (Kiniry et al., 1992 ; Cabelguenne et al., 1999), AquaCrop (Todorovic et al., 1999), AqYield (Constantin et al., 2015), WOFOST (Todorovic et al., 1999)…
- Or specific: Oilcrop-Sun (Villalobos et al., 1996), QSUN (APSIM) (Chapman et al., 1993), SUNFLO (Casadebaig et al., 2011)

However, crop models should be still improved to reduce the uncertainty due to model structure when predicting yield in future environments. Only some of these models have been adapted to simulate crop response to increased [CO2] and high temperatures. The impact of extreme events should be included in crop modelling approaches, otherwise there is the risk of strongly underestimating crop yield losses (Moriondo et al., 2011). CropSyst and STICS which both include the effects of elevated [CO2] on crop photosynthesis and transpiration have been extensively used. As pointed out by Andrianasolo et al (2016), only a few models explicitly consider seed oil content.

The combined effects of elevated [CO2], high temperatures, drought and nutrient status as simulated by the models have to be compared as it was recently done for wheat and maize in the recent AgMip international initiative. More effort is still necessary to make these models operational tools for climate change impact assessment and adaptation design. Uncertainty has to be considered in model inputs and outputs. Ensemble crop simulation protocols have still to be developed for sunflower crop.

To be improved, models should integrate more physiological knowledge on the combined effects of CO2, drought and temperature on crop production.

PHYSIOLOGICAL IMPACTS OF CLIMATE CHANGE ON PRODUCTIVITY

CO2 fertilization effect

Rising atmospheric [CO2] can affect the growth and yield of C3 plants, mainly through enhancement in the rate of photosynthesis and carbon assimilation (Griffin and Seemann, 1996). Various studies have been conducted worldwide on the response of different crop species to [CO2] which confirmed higher rate of photosynthesis, plant growth and yield due to elevated [CO2] exposure (Ainsworth et al. 2008; Taub et al. 2008). In C3 plants as sunflower, radiation, water and N use efficiencies are all expected to increase with [CO2]. It is known that C3 crops plants produce more biomass and harvestable products under high CO2 environment compared with C4 due to the enhanced rate of photosynthesis (Long et al., 2006). There is also adequate evidence that the CO2 fertilization effect will continue for C3 plants at least until the [CO2] reaches 750 ppm (Seneweera and Norton, 2011). The extent of this increase will depend not only on the short-term stimulation of photosynthetic activity but also on longer-term acclimation responses (Sims et al., 1999). Most of the studies on plant response to elevated [CO2] have been conducted in cereal crops (e.g. wheat), and very few reports are available about the response of oilseed crops, especially sunflower. However, during the two last decades, some studies on sunflower confirmed the typical C3 response of sunflower to elevated [CO2].

Sims et al. (1999) grew sunflowers in large controlled-environment chambers receiving ambient and twice-ambient concentrations of atmospheric CO2. Exposure to 2 x [CO2] enhanced rates of net photosynthesis in individual upper-canopy sunflower leaves by approximately 50%. Cheng et al. (2000) using a whole-system gas exchange chamber and a 13C natural tracer method observed that total daily photosynthesis, net primary production, and respiration were consistently higher under the elevated [CO2] treatment than under the ambient [CO2] one. Luo et al. (2000) grew sunflowers in large environmentally-controlled chambers receiving atmospheric [CO2] of 400 and 750 ppm. They observed that elevated [CO2] increased canopy light utilization by 32% and carbon uptake by fully 53%. De la Mata et al. (2012) observed that photosynthetic CO2 fixation was boosted on young leaves growing under elevated [CO2]. The above findings all suggest that sunflowers should become more efficient at absorbing sunlight and using its energy to convert CO2 into carbohydrates as the [CO2] increases in the future. Consequently net photosynthetic rates and biomass production should increase as well.

De la Mata et al. (2012) also indicated that elevated [CO2] could promote early leaf senescence in sunflower plants by affecting the soluble sugar levels, the C/N ratio and the oxidative status during leaf ontogeny. Additionally, De la Mata et al. (2013) concluded that elevated [CO2] alter enzymes involved in N metabolism at the transcriptional and post-transcriptional levels, thereby boosting mobilization of N in leaves and triggering early senescence in sunflower plants.

There are very few reports on the impact of high [CO2] on the quality of sunflower seed oil. High [CO2] could affect nutritional quality of sunflower due to the dilution effect (Jablonski et al. 2002 ; Taub et al. 2008). Pal et al. (2014) reported the impact of high [CO2] exposure (550 ± 50 ppm) on oil percentage and quality of two sunflower genotypes raised inside open top chambers. Elevated [CO2] exposure significantly influenced the rate of photosynthesis and seed yield (61–68 % gain in biomass and 35–46 % increase in seed yield for two genotypes), but mineral nutrient and protein concentration decreased in the seeds (-13

%). However, oil content increased significantly in cv. DRSF 113 (15 %). Carbohydrate seed reserves increased with similar magnitudes (+13 %) in both the genotypes under high [CO2] treatment. Fatty acid composition in seed oil contained higher proportion of unsaturated fatty acids (oleic and linoleic acid) under elevated [CO2] treatment (Pal et al., 2014).

These findings conclude that rising atmospheric CO2 in changing future climate can enhance biomass production and seed yield in sunflower and alter their seed oil quality. However, the beneficial effects of high CO2 can be negated by other climate factors such as increase in atmospheric temperature and pattern of precipitation (Ainsworth et al., 2008).

Drought effects

Drought is the main environmental factor limiting sunflower plant growth in a wide range of environments. Sunflower, being a crop with medium water requirements, has the ability to tolerate a short period of drought. However, water stress may inhibit plant growth, decrease developmental activities of the cells and tissues and cause a variety of morphological, physiological and biochemical modifications (Ahmad et al., 2014). As water deficit should increase with climate change in southern environments, negative impacts on leaf expansion, biomass accumulation and oil production are all expected. These effects of drought on sunflower yield have been extensively studied and reviewed elsewhere in the literature (e.g. Connor and Hall, 1997; Chimenti et al., 2002; Ahmad et al., 2014). Negative impacts on oil concentration and oil quality are also expected (Andrianasolo et al., 2016).

High temperature

High temperature affects numerous biochemical and physiological traits in plants. In sunflower, compared to cereals, few efforts have been devoted to exploring the effects of heat stress, even though the crop can be damaged by high temperatures during specific sensitive stages of development (Connor and Hall, 1997).

After submitting sunflower plants to a day/night regime of 33/19 °C for 16 to 42 days, De la Haba et al. (2014) observed decreased leaf growth (lower specific leaf mass, reduced leaf area) and soluble protein content during leaf life span relatively to control plants (70% vs. 45%, respectively). They suggested that high temperatures promote soluble protein degradation in leaves. It also reduces net photosynthetic rate possibly by decreasing the content in photosynthetic pigments and the stomatal conductance. Early senescence observed at high temperature would result from the accumulation of soluble sugars and the associated decrease in starch levels.

In sunflower, constant high temperature decreases final grain weight and oil yield (Harris et al., 1978). Chimenti et al. (2001) applied constant temperatures (12 to 40°C) during grain filling which resulted in a curvilinear response of the rate of embryo filling with a peak at 25°C; embryo-filling duration had a minimum close to 34 °C, and embryo size continuously decreased with increasing temperature above 25 °C. Direct effects of brief periods of heat stress during grain filling were investigated by Rondadini et al. (2003). They exposed the capitulae of plants growing at 25°C to temperatures of ca. 35, 37 and 40°C for seven consecutive days during grain filling. Brief periods of heat stress resulted in a lower seed weight, a greater percentage of pericarp, a lower oil content and an altered fatty acid composition. In addition, the period from 12 to 19 days after anthesis (daa) showed the greatest sensitivity to heat stress regarding embryo and grain weight responses, whereas the period of greatest sensitivity for oil quality was from 19 to 26 daa (Rondanini et al., 2006).

Temperatures higher than 31 °C at anthesis stage were demonstrated to be detrimental for sunflower yield, inducing a reduced pollen and floret fertility (Chimenti and Hall, 2001).

Astiz and Hernandez (2013) showed that temperatures over 26 °C were supra-optimal for pollen production in sunflower, even under well-watered conditions.

Multiple abiotic stresses

Independently, the impact of increased atmospheric [CO_2] and drought stress on crop growth and productivity was well documented, however the interaction between these two stresses are not well understood.

Vanaja et al. (2011) assessed the influence of enhanced [CO_2] (700 ppm) under both well-watered and drought stress conditions on plant water status, gas exchange and various root and shoot parameters of sunflower crop plants grown in open top chambers. Sunflower responded significantly and positively with eCO_2 under both water treatments for shoot:root ratio. Root volume showed a positive significant response with CO_2 concentration enhanced over ambient level and the increment in root volume was 146 %. The leaf water potential, stomatal conductance and transpiration showed a decreasing trend with drought stress and eCO_2 resulted in an ameliorative effect leading to higher net photosynthetic rates under drought stress. The beneficial effect of eCO_2 in sunflower by ameliorating the adverse effects of drought stress was confirmed.

Conroy et al. (1988) observed that sunflower plants were more drought-tolerant when water was withheld under conditions that favor osmotic adjustment, namely after previous acclimation to drought, when water deficits are slowly imposed or when [CO_2] was higher than 340 ppm. As water deficits increase, both leaf conductance to [CO_2] and the capacity of the mesophyll to fix CO_2 decline. Osmotic adjustment occurred during drought in expanded leaves which had been continuously exposed to 660 ppm or had been previously acclimated to drought. The effect was greatest when the treatments were combined and was negligible in non-acclimated plants grown at 340 ppm of CO_2.

CLIMATE CHANGE AND PATHOGENS

Climate change could influence development of the pathogen, host resistance and host-pathogen interaction (Coakley et al., 1999). Direct or indirect impacts (via canopy change) of climate change on sunflower disease complex are expected. However, very few information has been produced for sunflower diseases (Debaeke et al., 2014).

Primary infection could be limited by the lack of precipitation and evapotranspiration increase. To infect the plants, downy mildew *(Plasmopara halstedii)* requires about 50 mm of free water during the 10 days surrounding planting date. Sclerotinia head rot (*Sclerotinia sclerotiorum*) needs 42 hours of free water for infecting florets. Phoma black stem (*Phoma macdonaldii*) requires free water at the trough level for significant stem infection. Phomopsis stem canker (*Phomopsis/Diaporthe helianthi*) will develop initial leaf lesions if relative moisture exceeds 90 % during 36 hours within canopy. High temperatures or elevated VPD could slow down or stop the growth of fungi in the tissues as their thermal optimum often ranges from 15 to 25 °C. Several successive days with $T_{max} > 32$°C could be lethal for Phomopsis. At the same time some pathogens could be promoted by hotter and dryer conditions. *Macrophomina phaseolina* could be stimulated by low soil water content and temperatures within 28-30 °C range (Sarova et al., 2003). Premature ripening due to Phoma could be enhanced by dry conditions after flowering (Seassau et al., 2010).

The weakest vegetative growth of sunflower exposed to early soil water deficit could reduce the risk of primary infection by fungi that directly cause damage to leaves and stems (Debaeke et al., 2014). More precipitation in winter and elevated [CO_2] could promote plant growth and favour the development of associated diseases.

If sunflower move northward to be grown in new environments that are free of inoculum, less attacks are expected in a first time especially if sunflower is grown less frequently as a break crop.

Ecological conditions in the future will be probably less prone to the diseases responsible of yield losses today. But some dominance changes may occur between pathogens (and pathotypes) according to their thermal pLITERATURE and their dependency to free water. Pathogens with long conservation forms in the soil (e.g sclerotia) could better tolerate unfavourable periods. The damage due to systemic pathogens could be reinforced if plants are suffering from water stress.

CLIMATE CHANGE AND POLLINATORS

Sunflower, as an allogamic plant, needs insects on flowering, especially the honey bees and bumble bees for seed production (De Grandi-Hoffman and Watkins, 2000 ; Oz et al., 2009). Breeding system of self-incompatibility and pollen not well adapted to the transport by wind hinder the process of pollination by anemophily. Numerous experiments have found that a seed set as low as 10-20% results when pollinators are absent and plants self-pollinate, compared to up to 90% seed set in flower heads accessible to pollinators. However, cultivars have different levels of self-fertility, and many modern sunflowers are fully self-fertile. Cross-pollination may still be preferred, as it appears to give higher yields and better quality in terms of oil content. At the same time, collecting nectar and pollen by honey bees in sunflower crops is also essential to apiculture (Delaplane and Mayer 2000). Unlike other insects, bees visit a great number of flowers to fulfill the needs of their colony assisting pollination by the way (Müller et al., 2006).

Temperature, precipitation and extreme events associated to climate change could modify the activity of pollinators (Kjøhl et al, 2011). Having different climatic requirements, pollinators and plants may therefore respond differently to changes in ambient temperature. For example, increased spring temperatures may postpone plant flowering time while pollinators might be unaffected. As stated before, pollen fertility may be greatly reduced at high temperatures (Astiz and Fernandez, 2013), which increases the importance of prompt pollination of self-pollinated varieties during hot weather. Water stress resulting from climate change may decrease flower numbers and nectar production. Extreme climate events might have detrimental effects on both crop plants and pollinator populations. High temperatures, long periods of heavy rain and late frost may affect pollinator activity either by reducing population sizes or by affecting insect activity patterns. Sunny days with low wind speed and intermediate temperature are optimal foraging conditions for pollinators.

There is still clear evidence of declines in both wild and domesticated pollinators (e.g. honey bees) (Potts et al., 2010). Pollination is under threat from different kinds of environmental pressures including habitat loss and fragmentation, agrochemicals, pathogens, alien species, climate change and the interactions between them (Potts et al., 2010). Pollinator declines can result in loss of pollination services which have important negative ecological and economic impact that could significantly affect crop production and food security (Gallai et al., 2009). Because of cross-pollination in sunflower, seed production activity (for hybrids) and commercial grain production could be both affected by decline associated to climate change and other causes.

CROP ADAPTATION TO CLIMATE CHANGE

Plant breeding is considered to be a substantial tool for adaptation strategies to climate change (Ceccarelli et al., 2010). Breeding for new varieties better adapted to thermal shocks (heat, cold) and drought is often suggested as the major long-term adaptation. The breeding strategies aim at improved water efficiency, improved drought stress tolerance, and increased responsiveness to higher atmospheric [CO2] (Ceccarelli et al., 2010; Ziska et al., 2012). However, prospective results of plant breeding are unforeseeable and the impact assessment would strongly depend on the assumptions made on breeding advances (Grass et al., 2015).

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 cultivars (earliness), revising soil management, fertilization and plant protection practices, introducing or expanding irrigation. Crop management still offers a range of opportunities to cope with drought-prone conditions (Debaeke and Aboudrare, 2004).

In sunflower, planting date could be anticipated to escape water stress at flowering and during grain filling. In some Mediterranean regions, sunflower can be planted in late autumn or winter with good results in water use efficiency and yield (Gimeno et al., 1989; Soriano et al., 2004). In northern parts, earlier sowing date in spring was attempted with sometimes unsuccessful results (Alline, 2009). Varieties adapted to early planting with increased vigor should be selected to take advantage of this practice. Without irrigation, the search and use of cultivars with lower base temperatures and shorter thermal times for emergence will become of great importance. The compensation of reduced crop duration with increasing temperature could be searched by using long cycle cultivars combined with early sowing date.

Crop models have been applied in given situations or at a regional scale to simulate impacts of climate change on yield as a preliminary task for simulating possible adaptations. Guilioni et al (2010) using STICS model recommended to use late-maturing cultivars and early planting with some perspectives to increase yield in France. Donatelli et al. (2015) simulated simple technical adaptions with CropSyst model. Sowing date was shifted by either bringing forward or delaying sowing by either 10 or 20 calendar days with respect to the baseline sowing date. The other factor was the length of the biological cycle as a proxy for simulating varieties from different maturity groups. Growing degree days was manipulated to get a realistic variation of flowering and physiological maturity. These authors concluded that adaptation for rainfed sunflower was not completely effective under the 2030 time horizon in a large belt from central France to the most eastern area of Europe. However, it must be pointed out that such results were obtained via simple adjustment of technical management without exploring possibly improved varieties. Also, more favorable patterns of winter rainfall may lead to increased availability of water, hence maintaining the feasibility of irrigation.

Undoubtedly, supplemental irrigation is an effective way to maintain or increase sunflower yield (and oil concentration) in dry conditions (Rinaldi, 2001; Demir et al., 2006; Klocke et al., 2013) but future water resources could be limited because of competition among users. More water in winter could however be stored for securing summer irrigation when possible.

Rainfed sunflower crop production in Mediterranean environments depends to a large extent on strategies that avoid the intense summer drought. The use efficiency of scarce water resources should be increased by promoting soil conservation techniques e.g. mulching in no-till systems for reducing soil runoff and evaporation as was attempted in semi-arid regions for sunflower (Aboudrare et al., 2006).

Crop diversification (at field, farm or territory level) could be recommended as a self-insurance measure to cope with more uncertain and fluctuant conditions and bring resilience to the system. Sunflower could be more present in the situations where water resources are scarce. Double cropping could benefit from the longer cropping duration on an annual basis (Grass et al., 2015). Very early sunflower varieties could be planted after oilseed rape, barley or pea completing their cycle in late spring. However irrigation will be absolutely required for crop establishment while summer water availability could be restricted in some areas.

Model-based tools and site-specific technology should be developed to optimize, support and secure farmer's decisions. Adaptation could range from tactical fine-tuning to deep changes in the nature of cropping systems with impacts downstream on land use and agricultural sector activity (machinery, inputs, market).

REDUCTION OF GHG EMISSIONS WITH SUNFLOWER CROPPING

On average, the total emission of greenhouse gas (GHG) of sunflower in France is about 900 kg CO_2-eq ha^{-1}, according to a calculation based on the average input applications in France (BIO IS, 2010), the emission factors for the production and transportation of inputs used in France and from the tier 1 method of IPCC to estimate direct and indirect nitrous oxide emissions (De Klein et al., 2006) (Table 1). The emissions of nitrous oxide (N_2O) account for almost half of the total GHG emissions, while the fuel consumption and the mineral N fertilizers are respectively responsible for 23 and 22 % of the total. Overall in sunflower, almost 70% of the GHG emissions arise from N applications because the tier 1 method calculates N_2O emissions as a percentage of the amount of N applied on the field. Hence, the reduction of GHG emissions in sunflower should focus on both the improvement of N efficiency, in order to decrease the amount of N application, and on the control of NO_3^- leakage and NH_3 emissions because those N leakages from the field result in indirect N_2O emissions. Factors that control some soil properties, especially soil humidity and pH, could also contribute to decrease GHG emissions because they have a major role on N_2O emissions (Granli et Bøckman, 1994), but they are not taken into account in the tier 1 method. The reduction of fuel consumption, which is mainly due to soil tillage, would also significantly contribute to decrease the total GHG emission of sunflower.

The same pattern of GHG emissions is also observed in the main other crops cultivated in France (Figure 2). However, the shares of N fertilizer and N_2O emissions are higher in other crops, compared to sunflower, because the amounts of N applications are greater: 38 kg N ha^{-1} in sunflower (Table 1) vs. 97 to 189 kg N ha^{-1} in other crops (data not shown). Hence, the total emissions per hectare of other crops are 3 to 3.6 fold greater than that calculated for sunflower. For this reason, cultivating sunflower is an effective way to produce oilseeds with low GHG emissions, even though its seed yield is relatively low: the seed yields taken into account in the calculations, which are representative of the average values in France, are 2.39 t ha^{-1} for sunflower and 3.28 t ha^{-1} for rapeseed, resulting respectively in 376 kg CO_2-eq / t of seeds and 812 kg CO_2-eq / t of seeds (data not shown).

CONCLUSIONS

- Sunflower yield was simulated to potentially improve at northern latitudes with climate change, but with negative effects on yield at southern latitudes
- In the next future (2050), the elevated [CO2] in the atmosphere could compensate for negative impacts of high temperatures, water stress and reduced crop duration; the CO2 fertilization effect will not prevent yield decrease at 2070-2100 horizon.
- A wide range of genetic and agronomic adaptations have to be evaluated and combined.
- As a low GHG emitter, more attention should be paid on sunflower in future cropping systems.

Table 1 – Inputs used for sunflower cultivation in France, nitrous oxide and GHG emissions

Inputs and nitrous oxide emissions		GHG emissions (kg éq. CO_2 ha^{-1})
Mineral N fertilizers	38 kg N ha^{-1}	200.6
Mineral P fertilizers	29 kg P_2O_5 ha^{-1}	16.6
Mineral K fertilizers	22 kg K_20 ha^{-1}	11.6
Pesticides	3 kg ha^{-1}	23.1
Seeds	4 kg ha^{-1}	8.1
Fuel	67 l ha^{-1}	206.0
Seed drying	354 MJ ha^{-1}	9.3
Nitrous oxide	0.91 kg N-N_2O ha^{-1}	422.2
TOTAL		**897.6**

GHG emissions were calculated from mean input applications in France (BIO IS, 2010), the emission factors for the production and transportation of inputs used in France and from the tier 1 method of IPCC to estimate nitrous oxide emissions (De Klein et al., 2006).

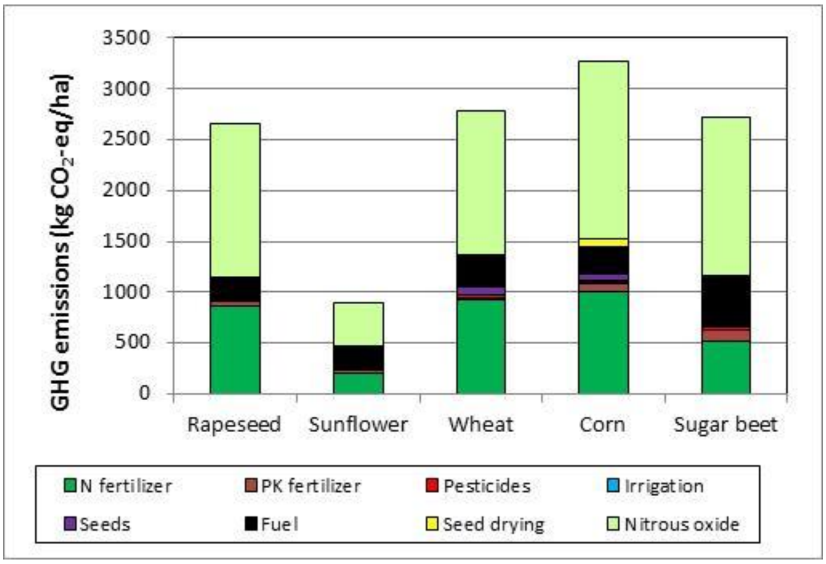

Figure 2 – GHG emissions of sunflower compared to other crops

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