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Dossier

Sunflower crop and climate change: vulnerability, adaptation, and mitigation potential from case-studies in Europe

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Abstract – Climate change is characterized by higher temperatures, elevated atmospheric CO_2 concentrations, extreme climatic hazards, and less water available for agriculture. Sunflower, a spring-sown crop often cultivated in southern and eastern regions of Europe, 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 alterations. Adaptations through breeding (earliness, stress tolerance), crop management (planting dates), and shifting of growing areas could be developed, assessed and combined to partly cope with these negative impacts. New cultivation opportunities could be expected in northern parts of Europe where sunflower is not grown presently and where it could usefully contribute to diversify cereal-based cropping systems. In addition, sunflower crop could participate to the mitigation solution as a low greenhouse gas emitter compared to cereals and oilseed rape. Sunflower crop 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.

Keywords: CO_2 / temperature / crop model / biotic stress / water deficit

Résumé – Culture du tournesol et changement climatique : vulnérabilité, adaptation et potentiel d'atténuation via des études de cas en Europe. Le changement climatique se caractérise par des températures élevées, de plus fortes concentrations atmosphériques en CO_2, des risques climatiques extrêmes et moins d'eau disponible pour l'agriculture. Le tournesol, culture semée au printemps dans le sud et l'est de l'Europe, pourrait être plus exposé à l'avenir aux fortes températures et à un déficit hydrique marqué dès la floraison, avec pour conséquences des pertes de rendement, une diminution de la teneur en huile et une altération de la composition en acides gras. Des adaptations sont possibles à court et moyen terme par la sélection (précocité, tolérance aux stress), la conduite de culture (date de semis) et le déplacement des zones de production, permettant de faire face en partie aux impacts négatifs attendus. Ainsi le tournesol pourrait être cultivé plus au nord participant utilement à la nécessaire diversification des bassins céréaliers. En outre, la culture de tournesol étant faiblement émettrice de gaz à effet de serre par rapport aux céréales ou au colza pourrait contribuer davantage à la solution climatique apportée par l'agriculture. Les modèles de culture devraient être revus pour mieux tenir compte de ces facteurs environnementaux émergents si l'on veut réduire les incertitudes dans les prédictions de rendement et de teneur en huile. L'avenir du tournesol en Europe est probablement lié à son potentiel d'adaptation au changement climatique, mais dépendra aussi de sa compétitivité et de son attractivité en tant que fournisseur d'énergie et d'aliments.
Mots clés : CO_2 / temperature / modèle de culture / stress biotique / déficit hydrique

1 Introduction

In Europe, sunflower is mostly cultivated in southern and eastern regions. In 2013, Russia, Ukraine (together 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

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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 partly 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 atmospheric CO_2 concentration (400 ppm today) may increase up to 660 ppm and 790 ppm in 2060 and 2090, respectively (IPCC, 2007, 2014). This is expected to raise global temperatures due to the CO_2 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 throughout Europe and the climatologists are speaking of climatic trend and not of natural inter-annual climatic 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 (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 parts. However, annual precipitation trends as well as seasonal precipitation patterns should vary regionally (Lotze-Campen, 2011). In northern Europe and most of the Atlantic region, mean winter precipitation should increase contrary to the Mediterranean area (especially its eastern part). 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 area and much of eastern Europe) due to the combined effect of warmer temperatures and less summer precipitation (Lotze-Campen, 2011). In addition, droughts will start earlier and last longer.

Therefore, in its traditional production areas, sunflower crop as a spring- and summer-sown crop will be exposed to major climate change and potentially impacted by water shortage and high temperatures (see below). Sunflower is commonly viewed as a drought-tolerant crop and consequently as a cropping opportunity for regions where water resources (used for irrigation) are decreasing and in situations where soil water deficit is expected to increase dramatically (García-Vila *et al.*, 2012). When water is fully available, maize or soybean are preferred, and sunflower is often restricted to marginal areas or non-irrigated farms (Debaeke *et al.*, 2008). 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, sunflower could break winter crop rotations where non-sustainable use of fertilizers and pesticides are currently practised.

For the major crops (wheat, rice, and maize) in tropical and temperate regions, local temperature increases of 2 °C or more, induced by climate change, will negatively impact yields if there is no adaptation (Porter *et al.*, 2014). No such broad evaluation was produced for sunflower crop in the last IPCC reports and scientific reviews (Yadav *et al.*, 2011). This justifies this preliminary review:

– of the impacts of climate change on sunflower grain and oil yields,
– of possible adaptation options, and
– of the contribution of sunflower to greenhouse gases (GHG) emissions.

2 Crop suitability

Sunflower cultivation is currently limited to southern Europe and parts of central/eastern Europe mainly for temperature reasons. A northward shift of southern crops suitability area is likely to occur as temperature steadily raises (Carter *et al.*, 1991; Olesen and Bindi, 2002). It is commonly admitted that the area suitable for crop growing may shift northward by 180 km per 1 °C increase in annual mean temperature (Seguin, 2003). In addition, sunflower could also become viable at higher altitudes than presently (shift of +150 m per 1 °C increase). 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 in those areas could also increase the soil workability in spring.

Most of the crop suitability studies are based on thermal requirements (base temperature and growing degree-days). Tuck *et al.* (2006) used climate scenarios based on four IPCC SRES emission scenarios (A1, 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 climatic models, sunflower will continue to be potentially grown in over 60% of southern 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).

Anyway, sunflower should take advantage of the improved thermal regime (higher summer temperatures) at northern latitudes. Sunflower is currently grown up of 62° N in the most temperature favored regions of southern Finland (Peltonen-Sainio *et al.*, 2009). Requiring 1100 °Cd (Tb = 5 °C) for completing their cycle (Niemelä and Tulisalo, 2000), very early sunflower varieties might be grown northern than 65° N in the next decades. Some studies explicitly considered the extension of sunflower crop to southern England as a possible adaptation to climate change (Bellarby *et al.*, 2010). 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 modeled.

3 Impacts on crop yield

At southern latitudes, temperature increases, precipitation decreases as well as increases in climatic inter-annual 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 deficit and heat stress, which will theoretically reduce yields, lead to higher yield variability, and probably reduce the agricultural area of this traditional crop in regions as Italy, Spain, Portugal, and southwestern France (Moriondo and Bindi, 2007; Moriondo *et al.*, 2011).

To document these threats and be more accurate at regional level, several simulation-based studies involving sunflower were recently published (Tab. 1).

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 (maturity group and sowing date). Both potential and water-limited yields were simulated for NUTS2 regions of EU-28. The average [CO_2] in the atmosphere was set to 355 ppm for 2000 (baseline), 400 ppm for 2020 and 420 ppm for 2030, accordingly to IPCC assumptions.

In terms of potential yield, the 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 (Donatelli *et al.*, 2012). On the other hand, in 2030 time window, a detrimental effect of climate change by 5–20% was simulated in southern parts of Europe (Spain, Italy, Hungary, Romania, and Bulgaria) which might be due to the reduction of radiation intercepted by sunflower canopies (with higher seasonal temperature causing an acceleration of senescence) and to the depressive effect of high temperatures on photosynthetic activity. On the contrary, the yield gain in northern France and Germany suggests that global warming may increase the length of the growing period and make cultivation conditions more favorable for sunflower growing under these latitudes as discussed above. From the warm 2030 scenario, a potential decrease in sunflower production of around 10% was expected for all important Spanish regions and from 4% to 8% in France depending on the regions (Fig. 1). Almost all regions of eastern Europe (Hungary, Bulgaria, and Romania) could be 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 Spain whereas in France cold and warm scenarios resulted in the same yield estimations for 2030 (Fig. 1).

Considering water-limited yields in 2020 (Fig. 2), the simulations show an improvement (with HadCM3) of sunflower yield at southern latitudes (Spain, Italy, Romania, and Bulgaria) with some patches of decline in France and Germany in 2020 (Donatelli *et al.*, 2012). These improvements can be directly linked to the higher precipitation prediction compared to baseline. By 2030 the improvements should get milder in southern European countries, and eastern countries should see a 10–30% yield decline (Fig. 2). Higher evapotranspiration coupled with less rainfall could explain this negative impact.

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 (Tab. 1). Attention must be drawn as crop simulation models, GCMs, Regional Climate Models (RCMs) and Greenhouse Gas Emissions (GGE) scenarios differed among studies, which led to contradictory and uncertain conclusions.

Tubiello *et al.* (2000) investigated with CropSyst and two GCMs the potential effects of doubling the atmospheric [CO_2] from 350 to 700 ppm on sunflower yields at two Italian locations. They concluded to limited changes for non-irrigated sunflower as a consequence of sufficient soil water refillment during winter fallow period.

Guilioni *et al.* (2010) used both SUNFLO and STICS crop models (both including CO_2 effects) to simulate baseline, next and far future climate (CLIMATOR project). They concluded to minor changes for 12 locations in France, the positive effects of increased atmospheric [CO_2] compensating for negative effects of water stress. However they predicted an increase of inter-annual variability during vegetative period. The potential extension of sunflower crop northward in France was confirmed as well. Crop duration was reduced by 4–6 days at flowering time and by 7–12 days at harvest per 1 °C increase of air temperature, as a function of RCM and genotype considered. The number of hot days (maximal temperature over 32 °C) during grain filling could increase from 8 (baseline) to 22 (far future) in Toulouse (southwestern France).

At the 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. The authors concluded that the increase in highest temperatures for the period 2071–2100 under A2 and B2 scenarios would result in an increase in the frequency of heat stress during anthesis with respect to the baseline (1961–1990). The yield losses 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 northeastern and southeastern regions and in the flat areas. In Portugal, Valverde *et al.* (2015) used a water balance approach combined with the Stewart method and CMIP3 climate projections datasets and simulated yield losses between 6% and 10% for the 2011–2041 period, and 11–19% for the 2041–2070 period. In these southern 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.

A recent study used the AQUACROP model from the FAO (Raes *et al.*, 2009) to simulate the yield and production of sunflower crop in Ukraine, Russia and Kazakhstan at the horizon 2046–2065 (Olivier *et al.*, 2016). Two climatic scenarios were tested: moderate warming according to CGM31 climatic model (+2.4 °C in 2065), severe warming according to MIROC3.2 climatic model (+4.3 °C in 2065). Only temperature and evapotranspiration were considered, precipitation being the same as the baseline and atmospheric [CO_2] change was not included. According to the moderate

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Table 1. Sunflower yield variation in Europe at different time horizons and without adaptation for a range of studies varying by crop models, scenarios of greenhouse gases emissions and regional climatic models.

Reference	GGE scenario	GCM/RCM	Baseline	Time horizon	Crop model	Simulation conditions	European regions	Yield variation
Harrison and Butterfield (1996)	UKHI UKTR 31–40 UKTR 66–75	UKHI UKTR	1961–1990	2023 2064 >2100	EuroSunfl	Water-limited yields (no irrigation)	Europe EU-15 North of 45°N South of 45°N	+4% to −39% +8% to −28% −11% to −25% +41% to −4%
Tubiello *et al.* (2000)	$[CO_2]$: 350 – 700 ppm (+4 °C; +10% precipitation);	2 GCM (GISS, GFDL) statistical downscaling						1952–1991 + weather generator (50 yr baseline)
n.a	CropSyst	Water-limited yields (no irrigation)	Foggia (Southern Italy)	0 to −6%				
Guilioni *et al.* (2010)	A1B (SRES)	GCM: ARPEGE + 3 downscaling methods	1971–2000	(FP) 2020–2050 (FL) 2070–2100	STICS	Water-limited yields (no irrigation)	6 locations in France	(FP) 0 to −14% (FL) +3% to −3%
Valverde *et al.* (2015)	A2, A1B, B1	16 IPCC models + 5 climate change scenarios	1961–1990	(1) 2011–2040 (2) 2041–2070	ISAREG	Water-limited yields (no irrigation	Portugal (Alentejo)	(1) −9% to −10% (2) −11% to −18%
Moriondo *et al.* (2011)	A2 (SRES) – 550 ppm B2 (SRES) – 700 ppm	RCM: HadRM3P	1961–1990 (350 ppm)	2071–2100	CropSyst CropSyst modified*	Water-limited yields (no irrigation)	Mediterranean zone +34° to +47° lat N -10° to +30 ° long E	A2: −6% to −21% B2: −10% to −22% A2: −24% to −46% B2: −25% to −41%
Donatelli *et al.* (2012)	A1B (SRES)	GCM/RCM: HadCM3/HadRM3 ECHAM5/ HIRHAM5	2000 (355 ppm)	2020 (400 ppm) 2030 (420 ppm)	CropSyst	Water-limited yields (no irrigation)	Europe (EU – 12 main producers)	HadCM3: 0 to −6% (2020); −6% to −14% (2030) ECHAM5: 0 to −20% (2020); −6% to −25% (2030)
Olivier *et al.* (2016)	A2 A1B	GCM31 MIROC32	1971–1990	2046–2065	Aquacrop	No precipitation and $[CO_2]$ changes	Ukraine Russia Kazakhstan	GCM31: −33% to +56% MIROC32: −87% to +63%

*Including heat stress effect on harvest index.

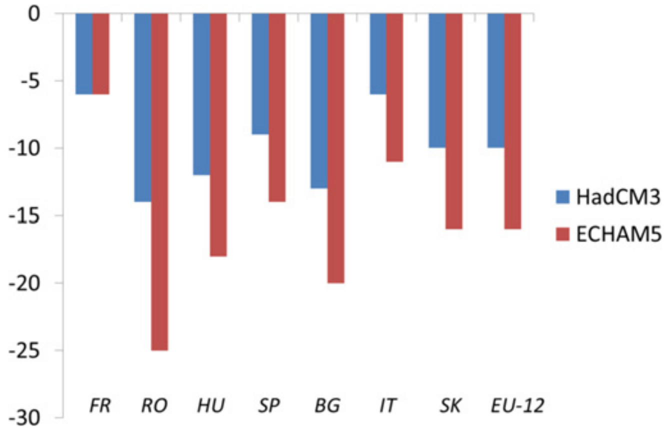


Fig. 1. Variation of sunflower production at 2030 horizon for 7 countries producing sunflower and for Europe (12 countries). From Donatelli *et al.* (2012). FR, France; RO, Romania; HU, Hungary; SP, Spain; BG, Bulgaria; IT, Italy; SK, Slovakia; EU-12 (7 previous countries + Austria, Czech Republic, Greece, Portugal, Slovenia).

scenario, total crop production would decrease globally by 3% (Russia and Kazakhstan production would be affected while production would increase in Ukraine). According to the severe scenario, total production would decrease by 50% with dramatic consequences on the world market as Ukraine would be deeply impacted.

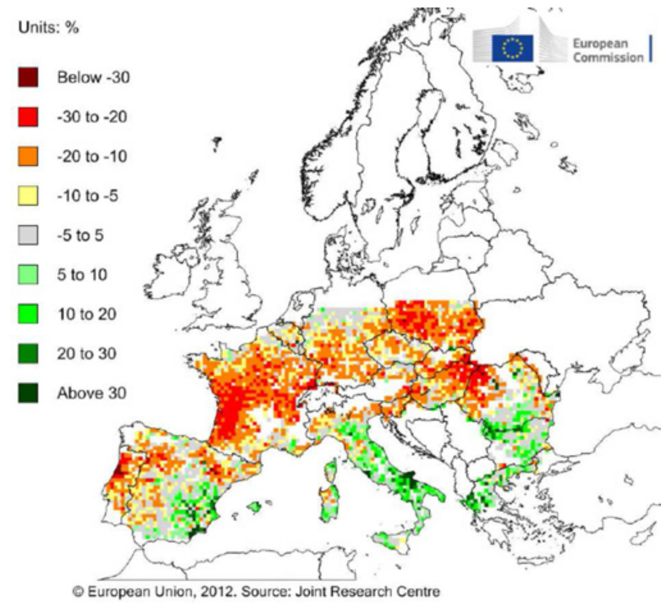
4 Crop models for exploring the impacts of climate change

Simple models have been used to map crop suitability based on growing degree-days (*e.g.* Tuck *et al.*, 2006). 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 (algorithms, databases, climate projections).

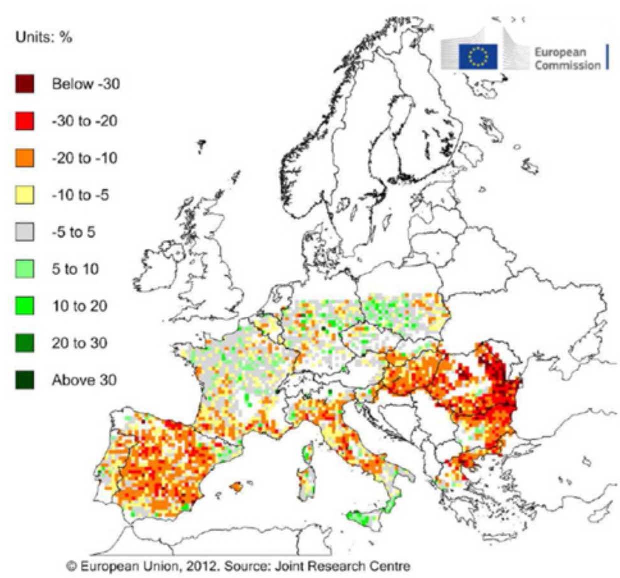
In simulation models, crop responses to climate change are predicted by modeling physiological processes (development, growth, and yield) as a function of [CO_2] and high temperature (Free-Air CO_2 Enrichment experiments, Ainsworth and Long, 2005; Temperature Free-Air Controlled Enhancement, Ottman *et al.*, 2012).

Crop models currently used for simulating sunflower yield in response to various environments are either: (i) generic (a single mode for multiple species): STICS (Brisson *et al.*, 2003), CropSyst (Stöckle *et al.*, 2003; Todorovic *et al.*, 2009; Moriondo *et al.*, 2011), EPIC/EPIC-Phase (Kiniry *et al.*, 1992; Cabelguenne *et al.*, 1999), AquaCrop (Raes *et al.*, 2009; Todorovic *et al.*, 2009), AqYield (Constantin *et al.*, 2015), WOFOST (Todorovic *et al.*, 2009) or (ii) specific to sunflower crop: Oilcrop-Sun (Villalobos *et al.*, 1996), QSUN (APSIM-sunflower) (Chapman *et al.*, 1993; Zeng *et al.*, 2016), SUNFLO (Casadebaig *et al.*, 2011).

Only some of these models embed equations to simulate crop response to increased [CO_2] and high temperatures, thereby enabling the risk of strongly underestimating crop



(a) HadCM3 scenario



(b) ECHAM5 scenario

Fig. 2. Relative change of sunflower yield in water-limiting conditions in 2030 using the 'warm' (HadCM3) and the 'cold' (ECHAM5) realisation of scenario A1B. No adaptation strategies are considered here (from Donatelli *et al.*, 2012).

yield losses in prospective scenarios (Moriondo *et al.*, 2011). However, CropSyst, EPIC, and STICS models have been extensively used and include the effects of elevated [CO_2] on crop photosynthesis and transpiration.

Consequently, more effort is still necessary to make these models operational tools for climate change impact assessment and adaptation design. To be improved, models should integrate more physiological knowledge on the single and combined effects of [CO_2], drought and temperature (*e.g.* temperature × drought interaction, Schoppach and Sadok, 2013) on crop production but also new outputs, as only a few models explicitly consider seed oil content (Andrianasolo *et al.*, 2016a).

A review by Parent and Tardieu (2012) focused on the relevance of current crop models to predict the genetic variability of yield under water deficit or high temperature. Concerning temperature, processes responses are often approximated with a linear function of temperature, thereby limiting the domain of validity of the model to the range of temperature in which the response is approximately linear (Parent and Tardieu, 2012). A simple first step for sunflower models should be to use curvilinear functions, which is expected to improve the prediction of crop development in high temperature conditions.

We also identified two other targets for increasing the accuracy of models; however, probably requiring more advanced ecophysiological modeling. First, environmental factors do not drive the same responses from plants during the crop cycle, even considering only vegetative and reproductive stages (*e.g.* for photosynthesis and transpiration, Andrianasolo *et al.*, 2016b). It was also reported that plants respond differently to stress patterns, *i.e.* long progressive *vs.* multiple short stresses (Caldeira *et al.*, 2014; Sadok, 2016). Current crop models implement a single plant response to each environmental factor, discarding distinct responses caused by development or multiple successive stresses (plant adaptation).

However, the current performance of sunflower crop models should be benchmarked, as it was recently done for wheat and maize in the AgMip international initiative (*e.g.* Martre *et al.*, 2015) before considering further implementation of described ecophysiological refinements.

5 Physiological impacts of climate change on productivity

5.1 CO_2 fertilization effect

Rising atmospheric [CO_2] 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 the increase of [CO_2] which confirmed higher rate of photosynthesis, plant growth and yield due to elevated [CO_2] exposure (Ainsworth *et al.*, 2008; Taub *et al.*, 2008). In C3 plants such as sunflower, radiation, water and N use efficiencies are all expected to increase with [CO_2]. It has been demonstrated that C3 crops plants produce more biomass and harvestable products under high CO_2 environment compared with C4 due to the enhanced rate of photosynthesis (Long *et al.*, 2006). There is also adequate evidence that the CO_2 fertilization effect will continue for C3 plants at least until the [CO_2] 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 [CO_2] have been conducted in cereal crops (*e.g.* wheat, maize, rice), 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 this oilseed crop to elevated [CO_2]. Exposure of sunflowers to twice higher CO_2 concentration than today in large controlled-environment chambers enhanced rates of net photosynthesis in individual upper-canopy leaves by approximately 50% (Sims *et al.*, 1999). Cheng *et al.* (2000) used a whole-system gas exchange chamber and a 13C natural tracer method to observe that total daily photosynthesis, net primary production, and respiration were consistently higher under the elevated [CO_2] treatment (750 ppm) than under the ambient [CO_2] one (400 ppm). Using the same experimental design, Luo *et al.* (2000) observed that elevated [CO_2] increased canopy light utilisation by 32% and carbon uptake by fully 53%. Again in 2012, De la Mata *et al.* (2012) observed that photosynthetic CO_2 fixation was boosted on young leaves growing under elevated [CO_2]. In an experiment where [CO_2] was increased from 399 to 746 ppm, Hui *et al.* (2001) measured an increase of daily total canopy carbon- and water-fluxes by 53% and 11%, respectively, resulting in a 54% increase in radiation-use efficiency (RUE) and a 26% increase in water-use efficiency (WUE) by the end of the experiment. More recently Rinaldi *et al.* (2015) showed that an increased [CO_2] from 370 to 760 ppm led to:

- an improvement of more than 60% in the net photosynthesis rate;
- a reduction of 7% of the stomatal conductance;
- a water saving of 0.074 $L\,m^{-2}$ (leaf) h^{-1} (due to the transpiration loss) and consequently
- an improvement of instantaneous water use efficiency (WUE) from 4.36 to 10.56 $mg\,CO_2\,g\,H_2O^{-1}$.

The above findings all suggest that sunflowers should become more efficient at absorbing sunlight, using its energy to convert CO_2 into carbohydrates and save water as the [CO_2] increases in the future. Consequently net photosynthetic rates and biomass production should increase as well. This was reported in several field studies in which significant increases in root and shoot biomass (from 24–68%) as well as final grain yield were observed with elevated [CO_2] (Tab. 2).

De la Mata *et al.* (2012) also indicated that elevated [CO_2] 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, these authors concluded that elevated [CO_2] alter enzymes involved in N metabolism hereby boosting mobilisation of N in leaves and triggering early senescence in sunflower plants (De la Mata *et al.*, 2013).

There are very few reports on the impact of high [CO_2] on the quality of sunflower seed oil. High [CO_2] 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 [CO_2] exposure (550 ppm) on oil percentage and quality of two sunflower genotypes grown

Table 2. Sunflower yield variation for a range of experimental studies controlling [CO_2] variation.

Reference	[CO_2] conditions (ppm)	CO_2 experimental design	Shoot biomass variation with eCO_2	Yield variation with eCO_2
Vanaja *et al.* (2011)	380–700	Open top chambers	+24% (well-watered) +49% (water stressed)	n.a.
Pal *et al.* (2014)	370–550	Open top chambers (field)	+61% to +68% (2 varieties)	+35% to +46% (2 varieties)
Srinivasarao *et al.* (2016)	380–550–700	Open top chambers (field)	+32% (700 ppm) +42% (550 ppm)	n.a.

inside open top chambers. Elevated [CO_2] exposure significantly influenced seed yield (Tab. 2) but protein concentration decreased in the seeds (−13%). However, oil content increased significantly in cultivar DRSF 113 (15%). Carbohydrate seed reserves increased with similar magnitudes (+13%) in both the genotypes under high [CO_2] treatment. Fatty acid composition in seed oil contained higher proportion of unsaturated fatty acids (oleic and linoleic acid) under elevated [CO_2] treatment (Pal *et al.*, 2014).

These findings confirm that rising atmospheric CO_2 in changing future climate can enhance biomass production and seed yield in sunflower but also alter protein and oil seed contents, and finally fatty acid composition. However, the beneficial effects of high CO_2 can be counter-balanced by other climate factors such as the increase in atmospheric temperature and unfavorable patterns of precipitation (Ainsworth *et al.*, 2008); this was also suggested by crop simulation studies (*e.g.* Guilioni *et al.*, 2010; Donatelli *et al.*, 2012).

5.2 Drought effects

Drought is the main environmental factor limiting sunflower plant growth in a wide range of environments in Europe and worldwide. Sunflower, being a crop with medium water requirements (Ky < 1), has the ability to tolerate a short period of drought, recover partially from stress and exhibit less than proportional reductions in yield with reduced water use (García-Vila *et al.*, 2012). By its high capacity to extract water from the subsoil, the crop has access to deeper resources (Cabelguenne and Debaeke, 1998). Its ability to regulate plant leaf area according to available water allows sunflower to control future water loss. Varieties of sunflower have been shown to exhibit contrasting responses to drought (Virgona *et al.*, 1990, Pankovic *et al.*, 1999). Sunflower genotypes may have conservative or productive stomatal responses resulting in various patterns of water use (Casadebaig *et al.*, 2008; Andrianasolo *et al.,* 2016b).

However, water stress inhibits plant growth, decreases developmental activities of the cells and tissues and causes a variety of morphological, physiological and biochemical modifications (Ahmad *et al.*, 2014). Since water deficit is likely to increase with climate change in southern environments, negative impacts on leaf expansion, biomass accumulation and oil production are all expected. These negative consequences of drought on grain 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) but negative impacts on oil concentration and oil quality have also been reported (Andrianasolo *et al.*, 2014, 2016a).

5.3 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 16–42 days, De la Haba *et al.* (2014) observed decreased leaf growth (lower specific leaf mass, reduced leaf area) and increase of soluble protein content during the 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 of photosynthetic pigments and the stomatal conductance.

In sunflower, constant high temperature decreases final grain weight and oil yield (Harris *et al.*, 1978). Chimenti *et al.* (2001) applied constant temperatures (12–40 °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 Rondanini *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 because they affect pollen production and floret fertility (Chimenti and Hall, 2001). Likewise, Astiz and Hernández (2013) showed that temperatures over 26 °C were supra-optimal for pollen production in sunflower, even under well-watered conditions. The effect of extreme temperature during anthesis was simulated by Moriondo *et al.* (2011) in a modified version of CropSyst crop model.

5.4 Interactions between temperature, water and CO_2

Independently, the impacts of increased atmospheric [CO_2], heat and drought stress on crop growth and productivity have been well documented. Heat and drought stress frequently occur together and in the future they will be associated to elevated [CO_2]. However, the interactions between these abiotic conditions and their effects on photosynthesis, plant growth and transpiration are still unclear in sunflower.

Recently Killi *et al.* (2016) grew two varieties of sunflower (drought tolerant and sensitive) under conditions of moderate (25 °C) or elevated temperature (35 °C) for 4 weeks prior to the imposition of water deficit. They observed than after being exposed to high temperature treatment, net photosynthetic rates and stomatal conductance of the drought sensitive variety were more affected by soil drying than after being acclimated to 25 °C. Consequently increased temperature could exacerbate the impact of drought stress in sunflower with some genotypic differences to explore.

Conroy *et al.* (1988) evidenced the role of CO_2 in the sunflower acclimation to water deficit. The authors observed that plants were more drought-tolerant when water was withheld under conditions that favor osmotic adjustment, namely when water deficits were slowly imposed or when [CO_2] was higher than 340 ppm. As water deficit increases, 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.

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 (Tab. 2). Root volume showed a positive response (+146%) with elevated [CO_2]. The leaf water potential, stomatal conductance and transpiration showed a decreasing trend with drought stress and elevated [CO_2] resulted in higher net photosynthetic rates under drought stress. Therefore a beneficial effect of elevated [CO_2] by ameliorating the adverse effects of drought stress was confirmed in sunflower. Tezara *et al.* (2002) concluded that elevated [CO_2] only marginally increased net photosynthesis with limited effects on metabolism of plants growing under water deficit; however, by slowing plant transpiration, CO_2 fertilization decreased the rate and severity of water deficit.

5.5 Multiple stress approach

A novel approach has recently been undertaken to model the impact of multiple abiotic stresses on sunflower oil yield (Mangin *et al.*, 2016). In this article, the authors developed stress indicators to characterize 14 environments for three abiotic stresses (cold, drought, and nitrogen) using the SUNFLO crop model and phenotypic variations of three commercial varieties. The computed plant stress indicators at variety level better explained yield variation than descriptors at the climatic or crop levels. The impact of stresses could be estimated to 347 kg ha^{-1} per day of cold stress, 137 kg ha^{-1} per day of drought and 247 kg ha^{-1} per kg of non-absorbed nitrogen. The genetic study based on the responses of 317 sunflower lines showed a strong genetic correlation between tolerance to drought and nitrogen but not between cold tolerance and the other abiotic stressors. This pioneer study performed in a French multi-environment trial network, showed that the cumulated cold stress was equivalent to 10 days and the cumulated drought stress to 35 days on average. Therefore, this indicates that although cold stress (during the vegetative period) has the largest relative impact on oil yield, drought stress was globally the most limiting factor in this multi-environment trial similarly to most sunflower cultivation areas.

6 Climate change and pathogens

Climate change could influence the development of pathogens, 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 comparatively to cereals for instance (Gulya *et al.*, 1997; 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 (Tourvieille de Labrouhe *et al.*, 2000). Sclerotinia head rot (*Sclerotinia sclerotiorum*) needs at least 39 h of free water for infecting significantly the florets (Lamarque, 1983). Phoma Black stem (*Phoma macdonaldii*) requires free water at the trough level for significant stem infection (Seassau *et al.*, 2010). Phomopsis stem canker (*Phomopsis/Diaporthe helianthi*) will develop initial leaf lesions if relative moisture exceeds 90% during 36 h 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 (Delos and Moinard, 1997).

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 favor the development of associated diseases.

If sunflower moves northward to be grown in new environments that are free of inoculum, more limited 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 preferences and their dependency to free water. According to Vear (2016), climatic

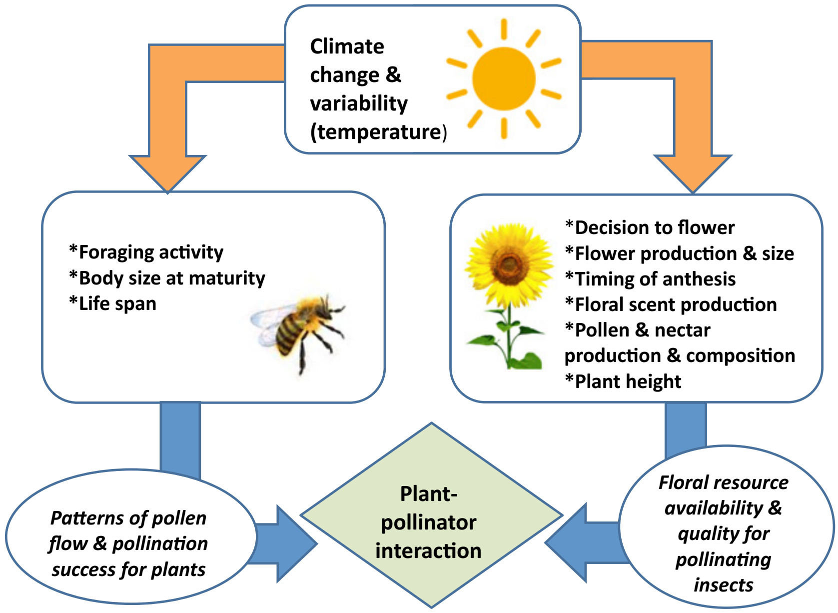


Fig. 3. Framework showing the impact of climate warming on the flowering process and insect activity and demography with consequences on floral resources and pollination success, both terms shaping the plant-pollinator networks (from Scaven and Rafferty, 2013).

change may be involved in the recent development of *Orobanche cumana* in France, since higher temperatures and absence of rainfall could favor broomrape development in sunflower. Pathogens with long conservation forms in the soil (*e.g.*, sclerotia) could better tolerate unfavorable periods. The detrimental effect of systemic pathogens which block the vessels could be reinforced if plants are suffering more intensely from water shortage in the future.

The development of models coupling crop growth and fungal epidemics in relation with crop management and climatic conditions has to be pursued to be able to predict the injury profile and crop damage in future conditions.

7 Climate change and pollinators

Sunflower, as an allogamic plant, needs insects on flowering, especially the honeybees and bumblebees for seed production (De Grandi-Hoffman and Watkins, 2000; Oz *et al.*, 2009; Chamer *et al.*, 2015). Breeding system of self-incompatibility and not well-adapted pollen type hinder the process of wind-pollination. 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 honeybees 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 (Scaven and Rafferty, 2013). 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 Hernández, 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. This was illustrated by Scaven and Rafferty (2013) in Figure 3: both physiological responses of flowering plants (on one side) and activity of insect pollinators (on the other side) can be modified by climate warning; these changes in turn will affect floral resources and pollination success for mutualists, hence shaping plant-pollinator networks.

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, insecticides, 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 (Chamer *et al.*, 2015).

8 Crop adaptation to climate change

8.1 Genetics and plant breeding

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 [CO_2] (Ceccarelli *et al.*, 2010; Ziska *et al.*, 2012). However, prospective results of plant breeding are unforeseeable and the impact assessment strongly depends on the assumptions made on breeding progress (Graß *et al.*, 2015).

During the past fifteen years, the sunflower yield increase through genetic advance has been slower than before, suggesting that current resources and breeding methods might not bring suitable solutions in a context of climate change (Vear, 2016). In order to face the challenges of delivering safe and high-quality food in a sustainable manner while maintaining yield and stability across different environments, a paradigm shift is needed in sunflower breeding.

The recent availability of the genome sequence (www.heliagene.org) of *Helianthus annuus* together with the breakthrough of the new breeding technologies in other crops (reviewed in Ricroch and Henard-Damave, 2016) is offering a favorable context to reinforce, through an optimization of the hybrid breeding process, the competitiveness of sunflower varieties. In addition to these novel technological resources, the large genetic diversity of sunflowers within *H. annuus* and across the *Helianthus* genius remains a very promising and largely untapped reservoir of new alleles to adapt sunflower varieties to social needs.

In this context, there is a great interest for breeding sunflower with high yield stability across different drought scenarios varying in the timing and quantity of water availability. Major actors in sunflower genomics from Canada, USA and France develop since a decade large genomics projects aiming at providing to the scientific community and breeders the necessary tools and resources to fulfill it.

More specifically in France, 15 partners including nine public laboratories with multi-disciplinary expertise spanning from social sciences, agronomy, genetics, and genomics, mainly from INRA, five major sunflower breeding companies (Caussade Semences, Maisadour Semences, RAGT2*n*, Soltis, and Syngenta), a biotech company (Biogemma) and the French technical institute in charge of oil-protein crops (Terres Inovia) joined within the SUNRISE (SUNflower Resources to Improve yield Stability in a changing Environment) consortium in an unprecedented effort over eight years (http://www.sunrise-project.fr/en/).

The project develops two approaches to identify the physiological, molecular and genetic components of resilience of sunflower hybrids to environmental variation with a special focus on water stress in the context of climate change (Debaeke *et al.*, 2015). First, the SUNRISE researchers develop a combined approach of crop modeling and quantitative genetics. On one hand, they take advantage of the eco-physiological processes represented in the SUNFLO crop model to estimate an average stress of control varieties in a multi-environment trial. This allows estimate the reaction norms of a panel of hybrids and identifies by a Genome-Wide Association Study the genomic loci controlling drought, cold and nitrogen stress tolerance. On the other hand, they identify the genomic loci controlling genotypic parameters of the SUNFLO crop model and predict yield and oil content of virtually recombining genotypes in a range of present and future climatic scenarios.

Secondly, SUNRISE researchers develop a systems biology approach to identify the molecular and genetic processes involved in drought tolerance and specially those allowing the systemic emergence of tolerance as a result of heterosis. For this, they produce a thorough molecular description of drought response in different organs (roots, leaves, and seeds) at the epigenetic, transcriptomic, proteomic, and metabolomic levels in various tolerant and sensitive genotypes including inbred lines and hybrids. Inference of the network describing these genetic interactions might allow identifying network patterns that trigger heterosis for drought tolerance. This second approach will produce some basic knowledge on drought tolerance that will be implemented in quantitative genetic models to improve Genome-Wide Association Studies (GWAS) approaches described above and Genomic Prediction of complex traits such as yield and tolerance to the studied abiotic stresses.

Altogether, these complementary approaches will accelerate sunflower hybrid process and help building new gene pools that will optimize their specific combining ability for productivity and stress tolerance in the context of climate change.

8.2 Adaptation of cultural practices

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 (Houmanat *et al.*, 2016). 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 choose late-maturing cultivars and early planting with some perspectives to increase yield in France. In south Italy, Tubiello *et al.* (2000) simulated 15% yield increase when sowing 2 weeks earlier than currently. Donatelli *et al.* (2015) simulated simple technical adaptations 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 or optimizing input management.

Undoubtedly, supplemental irrigation is an effective way to maintain or increase sunflower yield (and oil concentration) in dry conditions (Rinaldi, 2001; Göksoy *et al.*, 2004; Demir *et al.*, 2006; Champolivier *et al.*, 2011; Klocke *et al.*, 2013) but future water resources could be limited because of competition among users especially in the Mediterranean area (Falloon and Betts, 2010). More water in winter could however be stored (dams, lakes, etc.) 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 could be developed to optimize, support, and secure farmer's decisions. For example, the decision of the cultivar to be cropped (along with adapted management options) could be made in accordance with the most probable type of stress patterns occurring in the considered location. Such tool would allow a better spatial management of the genetic diversity, aiming to reduce genotype–phenotype mismatches thereby increasing production and stability of the target population of environments. We recently conducted a feasibility study where crop modeling was used to amplify the pedo-climatic variability experienced in cultivar evaluation networks and pointed that this approach allows recommending varieties according to environment types (Casadebaig *et al.*, 2016). Provided that simulation models feature previously detailed formalisms to deal with new environmental conditions, simulation-based approaches would be useful to explore potential adaptations to climate change (ideotype design, best management practices, etc.). 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).

Table 3. Inputs used for sunflower cultivation in France, nitrous oxide and GHG emissions.

Inputs and nitrous oxide emissions		GHG emissions (kg eq. 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_2O 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 (from De Klein *et al.*, 2006).

Dossier

9 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) (Tab. 3). 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 fertilization, 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 and 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 (Fig. 4). 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 (Tab. 3) *vs.* 97–189 kg N ha^{-1} in other crops (data not shown). Hence, the total emissions per hectare of other crops are 3–3.6 fold greater than that calculated for sunflower. For this reason, cultivating

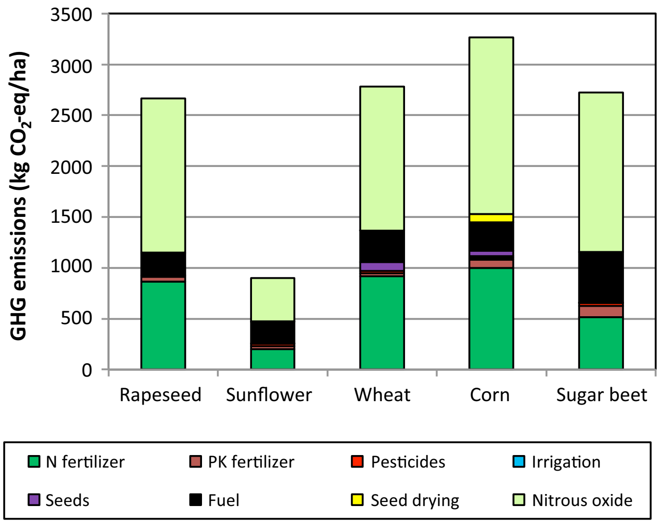


Fig. 4. GHG emissions of sunflower compared to other crops (from BIO IS, 2010).

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^{-1} of seeds and 812 kg CO_2 eq t^{-1} of seeds (data not shown).

10 Conclusions

Sunflower yield was simulated to potentially improve at northern latitudes with climate change, but with negative effects on yield at southern latitudes. By 2030 the AVEMAC analysis (Donatelli *et al.*, 2012) indicates potential decreases of production in various areas (southern and eastern Europe), if adaptation to climate change is not taken into account. In the next future (2050), the elevated [CO_2] in the atmosphere could compensate for negative impacts of high temperatures, water stress and reduced crop duration but the CO_2 fertilization effect will not prevent yield decrease at 2070–2100 horizon (Guilioni *et al.*, 2010). Numerous uncertainties still exist concerning biodiversity and biotic factors (birds, insects, soil macrofauna, fungi, etc.) that could affect sunflower production in the future. A wide range of genetic and agronomic adaptations have to be evaluated and combined at field, farm and landscape levels.

More attention should be paid on sunflower in future cropping systems as oil-protein, environmentally friendly crop, adapted to low-input production. Several opportunities for sunflower emerged with climate and global change:

– as a low emitter of greenhouse gases (low input crop),
– as a spring/summer break crop in (winter) cereal-based rotations of central and northern Europe (less pesticide use, mechanical control of fall emerging weeds, deep root exploration, etc.),
– as a possible double crop (very early cultivars) after barley, pea, oilseed rape contributing to C sequestration,
– as a C3 crop, benefiting from "CO_2 fertilization" (higher photosynthesis activity) and increasing water-use efficiency (lower water loss),
– as a (moderately) drought-tolerant crop, which can be grown without systematic irrigation, and be adopted in conditions where irrigation water is less available.

The future of sunflower in Europe is probably related to its potential adaptation to climate change (stress escaping, northward shift, double cropping, etc.) but also to its competitiveness and attractiveness for food and energy which must be enhanced through research and public policy.

Disclosure of interest

None declared.

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