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Sunflower agronomy: 10 years of research in partnership within the "Sunflower" Technological Joint Unit (UMT) in Toulouse☆, ☆☆

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Abstract – In order to make more efficient plant breeding and gain in competitiveness, the sector of oil-protein crops decided to intensify agronomic research on sunflower crop. The "Sunflower" Joint Technological Unit (Unité Mixte Technologique (UMT) "Tournesol", in French) was launched in the Toulouse area in 2006, associating closely INRA and Terres Inovia. First focused on improving oil production through an agronomic approach, the UMT was renewed in 2011 with a broader partnership and a more assertive orientation towards the development of decision-making tools. The objective of this paper is to highlight the relevance and productivity of this user-oriented research facility. The main results relate to (i) the co-construction of a simulation model (SUNFLO) that can be parameterized and manipulated by Terres Inovia engineers, (ii) the joint exploration of supra-field scales and new methods for agronomic diagnosis and yield forecasting based on remote sensing, (iii) the tuning and dissemination of operational decision rules, (iv) the production of essential knowledge on emergent and/or damaging fungal diseases, as well as on complex interactions between genotype, environment and crop management. After a concluding symposium in 2016, new requests for sunflower research were formulated by the participants. They also advocated for a diversification of crops to consider in order to better meet the needs of the whole oil-protein sector.

Keywords: sunflower / collaborative research / agronomy / decision support / oil concentration

Résumé – L'agronomie du tournesol : 10 années de recherche en partenariat dans l'UMT Tournesol à Toulouse. Afin de valoriser les avancées en sélection végétale et de gagner en compétitivité, la filière oléoprotéagineuse a jugé nécessaire d'intensifier la recherche agronomique sur le tournesol. L'Unité Mixte Technologique (UMT) « Tournesol » associant étroitement l'INRA et Terres Inovia a été mise en place en région toulousaine en 2006 à Toulouse. Tout d'abord centrée sur l'amélioration de la production d'huile de tournesol par une approche agronomique, elle a bénéficié d'un partenariat élargi lors de son renouvellement en 2011 affirmant une orientation plus marquée vers le développement d'outils pour la décision. Cet article illustre la pertinence et la productivité de ce dispositif en s'appuyant sur quelques résultats significatifs, en particulier : (i) la co-construction d'un modèle de simulation (SUNFLO) paramétrable et manipulable par les ingénieurs de Terres Inovia, (ii) l'exploration en commun des échelles supra-parcellaires et de la télédétection pour le diagnostic agronomique et la prévision des rendements, (iii) la construction et la diffusion de règles de décision opérationnelles, (iv) la production de connaissances sur des maladies émergentes ou nuisibles, ainsi que sur des interactions complexes entre le génotype, l'environnement et la conduite de culture. À l'issue d'un colloque conclusif en 2016, de nouvelles demandes à la recherche ont été formulées. Elles passent également par une diversification des objets d'étude pour mieux répondre aux besoins de la filière oléoprotéagineuse (the full text is available in French on https://www.ocl-journal.org/10.1051/ocl/2020006/olm).

Mots clés : tournesol / recherche collaborative / agronomie / aide à la décision / teneur en huile

☆ Contribution to the Topical Issue "Sunflower / Tournesol".
☆☆ The French version is available in "Supplementary Material".
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1 Introduction

In an increasingly constrained (climate change) and regulated context (French National plans "Ecophyto2" and Ambition BIO 2022, EU Nitrates Directive, "greening" of the Common Agricultural Policy, etc.), sunflower crop (*Helianthus annuus* L.) has many agronomic and ecosystem assets to be exploited, particularly for diversifying crop rotations, relaxing constraints on water resources and facilitating the agro-ecological transition (Pilorgé, 2010; Lecomte and Nolot, 2011; Debaeke *et al.*, 2017a, b). However, the species still needs to become more competitive in order to maintain its position vis-à-vis its competitors on the European and world oil markets. This requires increased productivity (both in quantity and quality) and more stable performance (robustness, resilience) in the context of efficient low-input crop management systems (Jouffret *et al.*, 2011).

The genetic progress that improved this species for many agronomic traits (Vear *et al.*, 2003; Vear, 2016) is still insufficiently enhanced by farmers and, in practice, the gap to the attainable yield remains significant or even widens (Jouffret *et al.*, 2011; Hall *et al.*, 2013; Sarron *et al.*, 2017) (Fig. 1). Intensifying agronomic research on this species is a key point in meeting this challenge and reducing or closing what is referred to as the "yield gap" in the literature (Hall *et al.*, 2013), which means the difference between attainable yield (measured on post-registration trials using recent cultivars) and on-farm yield.

This user-oriented approach must be conducted in close partnership between research and the oil-protein crop sector to be more effective and relevant. With this perspective, a close and long-term partnership has been built and expanded between INRA (now INRAE) and Cetiom (now Terres Inovia) since the late 1970s. In this article, we will focus on a particularly active phase of this partnership, which has involved these two actors since 2006 in the Toulouse area within the framework of the Mixed Technology Unit (UMT), simply named "Sunflower".

2 Genesis of the partnership in sunflower research between INRA and Terres Inovia

The partnership on sunflower between INRA and Cetiom was set up to sustain the amazing development of oil-protein crops in France and more particularly in the southwestern region in early 1980s; *de facto*, sunflower areas were multiplied by 11 in France, from 103 000 ha in 1980 to 1 145 000 ha in 1990.

Much work has been carried out at the INRA Agronomy Station of Toulouse-Auzeville in agronomy and crop physiology under the direction of R. Blanchet (Merrien, 2016), particularly on drought tolerance then on crop modelling in collaboration with geneticists and plant breeders from Clermont and Montpellier, but also with physiologists from the Toulouse University (ENSAT, ESAP, UPS) (Blanchet *et al.*, 1983, 1990). This work has been the subject of international collaboration in particular with the USA (Kiniry *et al.*, 1989, 1992), resulting in an adapted version of the EPIC crop growth model for sunflower (EPIC-Phase, Quinones *et al.*, 1990; Cabelguenne *et al.*, 1999).

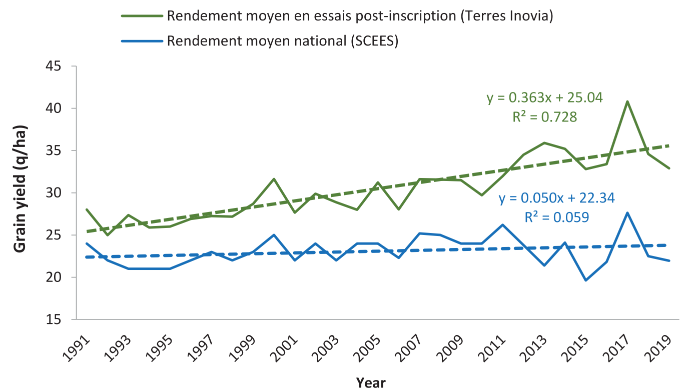

Fig. 1. Comparative sunflower grain yield trends on the 1991–2019 period: actual yield in blue (source: SSP, Ministry of Agriculture) vs average yield from post-registration trials in green; illustration of the yield gap and its magnitude with time (source: Terres Inovia).

During the 1980s, the activities of this consortium were presented and discussed at annual meetings bringing together the members of a research convention associating the oil-protein sector (Cetiom, SIDO, Onidol) and the various public research teams. Several publications (Blanchet *et al.*, 1981; Merrien *et al.*, 1981; Blanchet and Merrien, 1990; Merrien, 1992; Blanchet, 1994) and theses (Quinones Pedrosa, 1989; Texier, 1992) attest to this privileged partnership between agronomists from INRA Toulouse and Cetiom on sunflower crop physiology and its modelling.

Work also continued on the integration of sunflower in cropping systems and the development of crop management systems adapted to available water resources (Cabelguenne and Debaeke, 1998; Debaeke *et al.*, 1998; Debaeke and Nolot, 2000; Debaeke and Aboudrare, 2004; Aboudrare *et al.*, 2006). In 1998, a collaboration between INRA and Cetiom was built through a SIDO project on the effects of cropping systems on sunflower diseases, particularly phoma and phomopsis (Debaeke *et al.*, 2001; Debaeke *et al.*, 2003; Debaeke and Estragnat, 2003, 2009, Debaeke and Pérès, 2003).

Between 2000 and 2008, the "Productivity" projects supported by PROMOSOL assessed genetic progress in sunflower (Vear *et al.*, 2003) and paved the way for a new step of agronomic modelling that more explicitly integrated genetic variability (Debaeke *et al.*, 2004; Casadebaig, 2008; Lecoeur *et al.*, 2011). In order to adapt sunflower crop to early sowings (cold tolerance), studies at the interface of crop physiology and genetics were undertaken (Allinne, 2009, Allinne *et al.*, 2009, 2010). Genetic variability in the physiological response of sunflower to water stress was evaluated (Kiani *et al.*, 2007a, b; Maury *et al.*, 2011). In addition to yield, work has also focused on seed quality (Roche, 2005; Roche *et al.*, 2006; Ebrahimi *et al.*, 2009; Berger *et al.*, 2010) and the industrial valorization of by-products (Borredon *et al.*, 2011).

In 2005, in order to maintain active research on this species, and under the impulse of the oilseed industry and scientists, INRA focused its sunflower national research facility at the Toulouse Centre, around the "Sunflower 2010" action program. The presence of the main seed companies in the Toulouse region also influenced this decision. The entire program was intended to be interdisciplinary, relying on local skills in agronomy, ecophysiology, genetics, plant pathology, modelling and bioinformatics.

To carry out this project, the "Sunflower Genetics and Genomics" team from LIPM research unit was set up in 2007 with the aim of providing essential knowledge and tools in genetic and genomic resources. Currently, its programs aim to elucidate certain genetic and molecular mechanisms in order to adapt the crop to the biotic and abiotic environmental constraints, more particularly water stress, "cold" stress and resistance to the parasitic plant *Orobanche cumana* (broomrape).

As a continuity in the partnership for more than 30 years, Terres Inovia also strengthened its presence in this cluster by assigning to Auzeville, within the UMR AGIR (INRA), two engineers with the mission of building a UMT project, which was in 2006 a new opportunity proposed by the Ministry of Agriculture, Food and Forestry (Box 1) and supported by INRA (Guyomard *et al.*, 2011) for developing a sustained partnership and user-oriented research (Box 1).

Box 1. What is a UMT?

Mixed Technological Units (UMT) are scientific and technical partnership tools, created in 2006 (as a part of the agricultural modernization law) and supported by the Ministry in charge of agriculture, to jointly conduct, on a given geographical site, a research and development program with a national ambition, the results of which being operational and generalizable in the short and medium term. The UMTs promote synergies between researchers and engineers through the specific features of their activities: same location and common governance, co-construction of the national scientific program, pooling of technical and human resources, mix and complementarity of skills. On its theme, each UMT makes it possible to offer a unique and recognized entry into research and development for its various public and private sector partners. With no legal entity, an UMT is composed of at least one qualified technical institute and one public research organization or higher education establishment. UMTs are issued from calls for proposals. The projects must be in line with the scientific priorities of the two partner institutions. The expected outputs are the development of models, decision support tools, exploitation and management of databases, possible patent applications, co-authored publications in recognized scientific or technical journals, and deliveries to companies. In 2019, there were 17 UMTs for the agricultural sector (about half in the plant sector) with a strong contribution of INRA in most of them (https://agriculture.gouv.fr/developpement-agricole-et-rural-reseaux-et-unites-mixtes-technologiques).

3 Structuration of the sunflower research program in the Toulouse area today

The "Sunflower" UMT, which focuses on improving sunflower oil production through an agronomic approach, was approved in 2006 for a period of 5 years and then renewed with an expanded partnership in 2011 with a more assertive orientation towards the development of decision-support tools for crop management and variety assessment. Led by Terres Inovia, between 2006 and 2016, it brought together INRA (UMR AGIR – co-pilot – and the LIPM's Sunflower Genetics and Genomics team), INP-ENSAT, INP-PURPAN and CESBio, the latter on a program using satellite remote sensing to forecast sunflower yields.

The activities of the Toulouse research cluster dedicated to sunflower were structured around three main components: (i) acquiring genetic, genomic and physiological knowledge on the relationships between sunflower and water, sunflower and its disease complex, and grain and oil quality, (ii) by mobilizing different approaches or tools: modelling, remote sensing, phenotyping, genomics and development of genetic resources, in order to (iii) lead to operational results for breeders (*e.g.* Sunrise project) and/or for advisers (UMT project) (Fig. 2).

Multidisciplinarity and the pooling of resources are two strengths of this research system. Indeed, the work carried out is pluri- and even interdisciplinary: agronomy, ecophysiology, pathology, genetics, genomics, applied mathematics, technology, economics... In the same way, research resources are shared between the partners: networks of farmer's fields, field experiments, greenhouses, growth chambers, high-throughput phenotyping platforms, laboratories, databases, models...

The UMT's research program has led to the emergence of collaborations with the RECORD platform of the INRA Centre in Toulouse (Bergez *et al.*, 2013), but also with seed companies, agricultural cooperatives, ACTA, GEVES, SRAL Midi-Pyrénées, the Midi-Pyrénées Regional Chamber of Agriculture, RMT Modélisation, UMT "Water" and UMT CAPTE... During these years, international collaborations were also reinforced in agronomy, especially with Argentina (Unidad Integrada de Balcarce) which federates similarly to our cluster several organizations such as Conicet (research), INTA (extension) and the University of Mar del Plata (education).

Research work on sunflower agronomy would not have been possible without a variety of financial supports from the Ministry in charge of agriculture (*via* the DGER for the UMT basic support and CASDAR funds for 5 research projects), INRA (Agriculture Scientific Direction, Environment and Agronomy Scientific Division), Terres Inovia (including the co-funding of 5 theses), the Midi-Pyrénées Region (infrastructures, support for 3 theses and projects), the ANR (*via* the SUNRISE Investment Program for Future, the MicMac Design project or the PROMISES project of Carnot Plant2Pro, for example), the PROMOSOL association (SUNFLO-Maladies, SUNFLOWER-Pest, DEMELER projects), and the GIS GCHP2E (internship grants). The Agri Sud-Ouest Innovation and Competitiveness Cluster has also labelled several projects.

This close partnership is a concrete expression of the continuation of the historic relationship between research and the sunflower sector, with research that is geared towards meeting societal challenges and turned towards main stakeholders (breeders, consultants, producers and processors).

4 Some significant works resulting from the collaborative research in the "Sunflower" UMT

In this article, we will focus on research conducted in the field of agronomy, ecophysiology and plant pathology within the framework of the close partnership between UMR AGIR

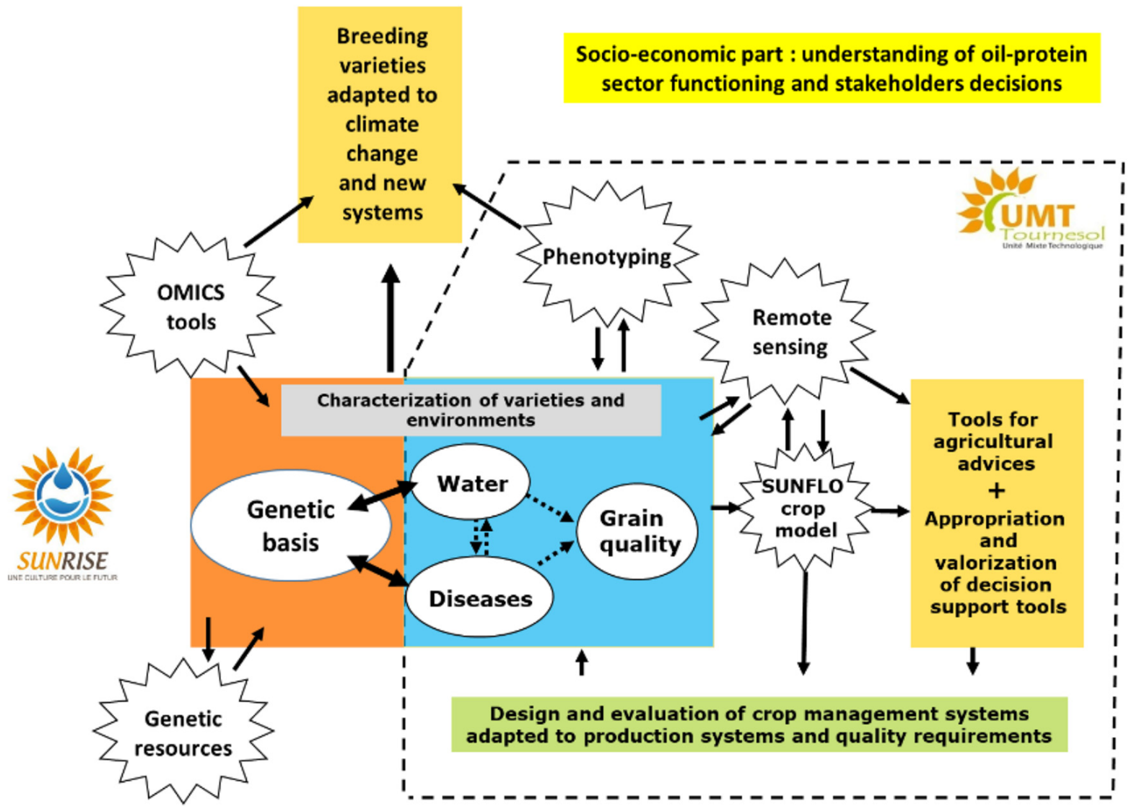

Fig. 2. Organizational chart of sunflower research activities within the Toulouse cluster and positioning of the "Sunflower" UMT (2006–2016).

(INRA), CESBio (CNRS, Toulouse University) and Terres Inovia within the "Sunflower" UMT platform by illustrating 5 representative actions conducted along the 10 years of close collaboration.

4.1 Building together an agronomic model that can be used by Terres Inovia for diagnosis, advice and varietal assessment

Several experiments had been attempted as early as the 1990s to import the agronomic modeling of sunflower within the routine activity of a technical institute such as Terres Inovia (*e.g.* Heol software based on EPIC – Texier, 1992; STICS Sunflower, Brisson and Levrault, 2010). These attempts had not led to the operational integration of a crop model into the practice of engineers, whether for studies (*e.g.* optimal irrigation strategies), end of season analysis or collective advices. The complexity of the functioning of the crop growth models, their "black box" side and the impossibility of easily parameterizing them from current experiments limited their practical interest and consequently their appropriation by Terres Inovia (Flénet *et al.*, 2008). Moreover, these models lacked varietal sensitivity, on the one hand, and a consideration of grain quality, on the other hand, thus reducing the scope of applications.

It is in full awareness of these past difficulties that the SUNFLO model (Casadebaig *et al.*, 2011) was developed within the UMT with a thesis co-funded by INRA and Terres Inovia (Casadebaig, 2008). Based on robust ecophysiological formalisms, its construction followed a principle of parsimony both in the description of the processes and in the form of the equations to be parameterized. Only the necessary and sufficient knowledge was introduced. When a certain complexity was required (*e.g.* a vertically distributed representation of the plant leaf area instead of a big leaf approach), it was justified either by a gain in precision without increased parameterization effort, or by the possibility of accessing to outputs of diagnostic value: for instance, by comparing the observed or simulated leaf profiles under environmental stress conditions with the potential varietal profile in non-limiting conditions, it is possible to identify the importance and timing of stress. One of the original features of SUNFLO is that it describes the intraspecific variability of phenotypes by means of about ten so-called "varietal" parameters, all of which being measured according to a standardized protocol (Debaeke *et al.*, 2010). A large number of parameters are directly accessible from several platforms set up by Terres Inovia for the post-registration evaluation of varieties (Casadebaig *et al.*, 2016a). Parameters of response to water stress require the use of an outdoor pot platform (Heliaphen) developed by INRA in Auzeville but open to Terres Inovia for the evaluation of new varieties (Blanchet *et al.*, 2016, 2018). In addition, the soil module, which is limited to water and nitrogen availability, uses a small number of variables accessible to users either by direct measurement or *via* soil maps or databases from the technical institutes (*e.g.* SoilBox). It also makes the field experimenter aware of the

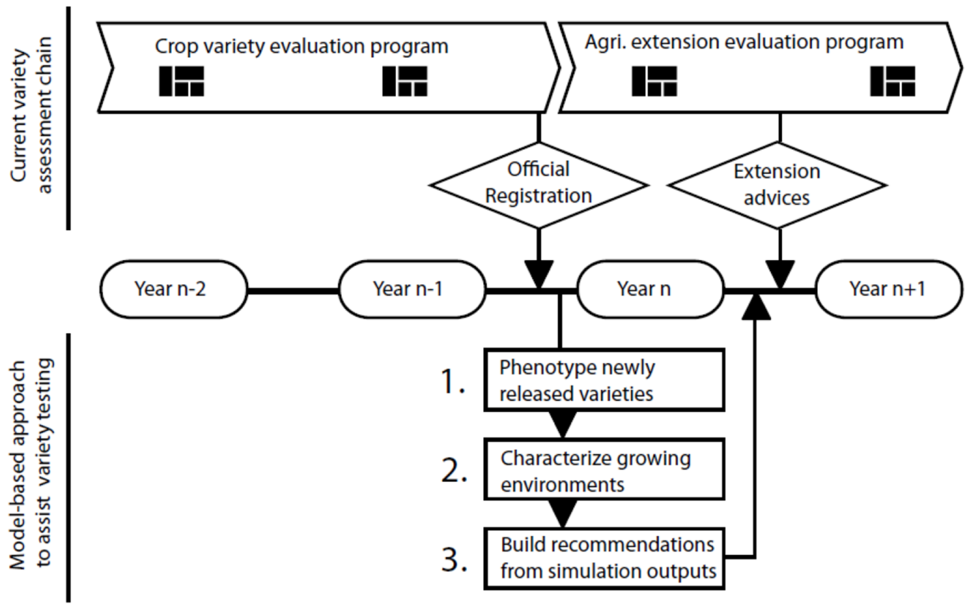

Fig. 3. Role of crop modelling in the variety evaluation chain (Casadebaig *et al.*, 2016a).

need to observe the depth of soil accessible to the roots instead of relying on an average available soil water content that is difficult to quantify at once. This has also resulted in soil characterization campaigns on the GEVES and Terres Inovia variety testing platforms. Thus, SUNFLO provides access by calculation to criteria that are difficult to measure, such as the stress levels perceived by the crop throughout the cycle (water deficit, nitrogen deficiency, effect of extreme temperatures), which have a diagnostic value in the frame of crop environment characterization and can be used in particular to predict the performance of varieties (Jeuffroy *et al.*, 2014; Landré *et al.*, 2020).

The predictive quality was assessed by comparing simulations with numerous field observations (> 1000 plots) from Terres Inovia post-registration networks over the past 10 years (Debaeke *et al.*, 2010; Casadebaig *et al.*, 2016a). The model has thus demonstrated that it can be implemented on plots with minimal information accessible to a multi-environment trial manager. Depending on the quality of the data used to describe the soil and the proximity of weather recording stations, the gap between simulation and observation (relative root mean square error on yield prediction) of the model is between 15 and 30%. Comparison of the varietal rankings obtained through experimentation or simulation indicates that the model is capable of significantly differentiating the performance of the varieties evaluated in the field, especially when they differ significantly by phenotypic parameters (growth and development).

The SUNFLO model has been integrated into various prototype tools for managers of variety evaluation networks from the private and public sectors. The understanding and exploitation of variety adaptation mechanisms, accessible through these tools, concern both agricultural development and varietal improvement. For agricultural development, the challenge is to make better use of cultivated genetic diversity by developing site-specific varietal advice, taking into account both local production conditions and climatic uncertainty (Casadebaig *et al.*, 2016a). For varietal improvement, the challenge is rather to use simulation to explore a large number of combinations of varietal characteristics (traits, ideotypes) and to identify those that would be the most interesting for developing new varieties taking climate change into account (Casadebaig and Debaeke, 2008, 2012).

Considering genotype-environment-management interactions (GEMI) makes it possible to improve varietal assessment and advice in a context of increasing diversification of both cropping systems and production objectives. In this case, dynamic modelling could usefully assist the prevailing and exclusive experimental approach used in variety evaluation, both for the registration of varieties and for information useful for their post-registration deployment (Debaeke *et al.*, 2011; Casadebaig *et al.*, 2016a).

Within the framework of projects supported by the CTPS in 2007 and 2010, we developed and tested an evaluation approach using the SUNFLO model at the various stages of the release process. This approach consisted in three steps (Fig. 3):

– routine implementation of phenotyping for new registered varieties;
– evaluation of the capacity of the SUNFLO model to simulate the performance of varieties in the national registration and post-registration networks (absolute or relative yield, oil concentration);
– use of the model capacity to explore a broad climatic basis in order to best position varieties and crop management according to soil conditions (available soil water content).

In addition, on these basis, we have co-constructed a prototype tool for varietal evaluation (VARIETO) with the network managers of GEVES and Terres Inovia (Debaeke *et al.*, 2012b). The main applications for this tool were the agronomic diagnosis of actual trials (*e.g.* identification of water stress periods experienced by varieties) (Debaeke *et al.*, 2012c), pooling of trials by soil type or stress profiles, analysis

Conseil de densité de semis

	Objectif de densité levée (optimum vis-à-vis du rendement et de la richesse en huile)	Cas général	Conditions optimales (lit de semences, conditions de levée, risque très faible de parasitisme et/ou déprédation[3])
		Taux de levée indicatif	
		75 %	85 %
Conditions très contraintes en eau (sols superficiels et sols intermédiaires en région méditerranéenne[1])	50 000 plantes/ha	65 000 graines/ha	60 000 graines/ha
Conditions moyennement contraintes en eau (sols intermédiaires hors région méditerranéenne, tournesol irrigué en sol superficiel)	55 000 plantes/ha	70 000 graines/ha	65 000 graines/ha
Conditions faiblement contraintes en eau (sols profonds, tournesol irrigué en sol intermédiaire ou profond) et zones "fraîches" et/ou à fin de cycle humide[2]	60 000 plantes/ha si écartement entre rangs ≤ 60 cm	75 000 à 80 000 graines/ha si écartement entre rangs ≤ 60 cm	70 000 graines/ha si écartement entre rangs ≤ 60 cm
	50 000 à 55 000 plantes/ha si écartement large[4]	65 000 à 70 000 graines/ha si écartement large[4]	60 000 à 65 000 graines/ha si écartement large[4]

1 : Région méditerranéenne : à climats méditerranéen et méditerranéen dégradé.
2 : Zones avec culture de variétés précoces à très précoces avec une fin de cycle fraîche et/ou humide (exemples : Lorraine, Champagne, Picardie, bordures de l'Atlantique et de la Manche).
3 : Parasitisme : limaces, larves de taupins… ; déprédation : oiseaux (pigeons), lapins, lièvres…
4 : Les écartements entre rangs ≤ 60 cm sont les plus adaptés au tournesol.

Fig. 4. Excerpt from Terres Inovia's plant density advice from Annual Sunflower Handbook https://www.terresinovia.fr/documents/20126/453413/Guide_tournesol_Terres-Inovia2019.pdf.

of the representativeness of networks with respect to actual production conditions (Debaeke *et al.*, 2012a), and comparison of the performance of varieties of different release generations. Some VARIETO functionalities have been tested by GEVES in particular. This prefigures the prototyping of a decision support tool better connected to environmental databases and variety characteristics in order to inform varietal choice by production situation.

4.2 Developing new crop management systems

In order to develop new crop management systems for sunflower, several approaches were carried out by coupling (i) classical multi-factorial experimentation (*e.g.* a range of plant densities applied to different varieties), (ii) process-based modelling with SUNFLO to simulate different "yield-factor level" response curves, (iii) agronomic diagnosis in numerous farmers' plots and (iv) "cropping system" trials in a limited number of experimental stations from INRA and Terres Inovia.

With regard to sunflower population density, an original approach was undertaken, coupling the analysis of real data from 38 Terres Inovia experiments and the analysis of virtual data from simulations with the SUNFLO cropping model. As a whole, more than 140 000 combinations between 16 varieties, 4 sites, 35 climatic years, 3 soil water reserve levels, 3 sowing dates and 7 stand densities were generated, providing access to a virtual database that was not possible to generate with field experiments and is very powerful for interaction analysis (Casadebaig *et al.*, 2016b).

This approach has shown that an increase in plant density in areas with high water stress (*e.g.* shallow soils) is not valued and has led to the proposal of optimal densities for yield and oil concentration according to the level of water stress in the plot (soil depth, climatic zone, irrigation or not).

Terres Inovia produced new rules and references to decide on sunflower plant density, which were more precise and profitable. They were published in the Sunflower Handbook distributed each year by Terres Inovia (Lecomte and Mestries, 2016) (Fig. 4).

Similarly, we have shown by simulation with SUNFLO that an average yield gain of 5.7 q/ha per 100 mm of irrigation is obtained with responses ranging from 1.6 to 11.5 q/ha with the production situation and that the strategy with an application at stage E4 (pre-flowering) is the most efficient from an agronomic point of view because it plays on the often limiting leaf area in shallow to moderately deep soils (Champolivier *et al.*, 2011a).

4.3 Integrating agronomic factors in the analysis and prediction of disease incidence

Sunflowers have a special place in low pesticide-dependent cropping systems because of their low treatment frequency index (average TFI of 2.3 without seed treatment; source: Agreste – SSP – Enquête Pratiques Culturales 2014) and spring-summer cycle that breaks up winter crop sequences. In some regions, the "oilseed rape-wheat-barley" winter rotation covers more than 30% of the sown area, which deserves more diversification in sowing periods. However, the sunflower disease complex, which is diversified and evolving, plays a significant role in the yield gap (Fig. 1). It has therefore been the subject of special attention within the UMT because its control is a key point in stabilizing production. Initial work focused on acquiring basic knowledge on fungal diseases: epidemiology, genetic determinism of sunflower resistance, impact of crop management on their expression, etc. In addition to these targeted actions, the originality of the work undertaken lies in taking into account the disease complex as a whole through modelling. The ultimate objective is to propose agroecological crop protection strategies (Deguine *et al.*, 2017).

4.3.1 Evidence of strong effects of crop management on disease expression

The onset (incidence) and development (severity) of a disease are the result of interactions between the pathogen, its host plant and their environment: soil, climate and crop management. To avoid (or at least limit) injury (symptoms) and damage (loss of yield and crop quality) to the crop, it is possible to intervene at three levels of the disease cycle: (i) avoiding the occurrence of the risk by limiting the inoculum reservoir, (ii) preventing the risk from occurring, and (iii) limiting the occurrence of injury and damage. Sunflower canopy management can play a significant role at each of these stages and thus contribute, in association with varietal choice, biological control or even chemical control (as a last resort), to effective and sustainable control of the main sunflower diseases (Mestries *et al.*, 2011; Debaeke *et al.*, 2014).

The research carried out within the framework of the UMT focused on two main sunflower diseases that are strongly influenced by crop management: phomopsis (*Diaporthe helianthi*) and phoma (*Leptopshaeria lindquistii*). They mobilized teams from INRA and Terres Inovia from 2007 to 2012 on agricultural fields, experimental stations and greenhouses. During two seasons with favourable conditions for phoma infection, the inoculum reservoir was evaluated at 60 000 fungus fruiting bodies on average per m^2 of soil surface area in agricultural plots. This was the first time that the primary inoculum of phoma was quantified in this way (Descorps *et al.*, 2012). No-tillage techniques (shallow tillage between 5 and 15 cm deep or very shallow tillage at less than 5 cm depth) do not seem to reduce the inoculum potential for the following year compared to direct seeding. Crop practices related to sowing (sowing date and density), N fertilization and irrigation and their interactions also have a strong influence on the appearance and development of the two diseases, but may play a different role (thesis of M. Desanlis, 2013): the microclimate resulting from canopy growth and soil covering (marked effect of stand density) thus plays a much greater role in the establishment of phomopsis than of phoma, whereas the nitrogen nutrition status of the plants seems to be more decisive in the progression of phoma symptoms on stem and collar than in the development of phomopsis. Finally, the conditions for the appearance of antagonism between phomopsis and phoma have been specified, as phoma settles at the petiolar insertion and can block the passage of phomopsis on the stem (Desanlis *et al.*, 2013) (Fig. 5).

This knowledge has been partially integrated into crop-disease interaction simulation models (SUNFLO-Diseases), which will eventually make it possible to develop decision support tools for agricultural advisory stakeholders.

4.3.2 better characterization of the premature ripening syndrome

Premature ripening (or death) sunflower is the most damaging form of Phoma black stem. North American research teams were the first to suggest a set of probable causes to explain this syndrome (Donald *et al.*, 1987; Gulya *et al.*, 1997): the presence of a bulk of pathogens including phoma, the effects of soil and climate, and an influence of crop management (nitrogen fertilization in particular). Research conducted in Toulouse as part of C. Seassau's thesis (2010) involving field, greenhouse and laboratory experiments confirmed the major role of phoma in this syndrome. The criteria for more accurately diagnosing premature death caused by phoma were defined: presence of phoma necrosis at the base of the stem, sudden wilting of the foliage and accelerated senescence 15 days to 1 month before physiological maturity, then root system degradation (Fig. 6). The effects of crop management on premature ripening were quantified: a relationship expressing the percentage of wilted plants in a plot according to the crop's nitrogen nutrition index (NNI) and the water satisfaction rate (WSR) was thus established (Seassau *et al.*, 2010a). This relationship illustrates the importance of adjusting nitrogen fertilization (NNI should be less than 0.8 on a 0–1 scale) and maintaining a satisfactory water supply (WSR should be more than 70%) during the post-anthesis phase on the onset and severity of this syndrome. Varietal tolerance and low stand density are two other determining factors of crop management to limit the incidence and severity of the disease (Seassau *et al.*, 2012). From a physiological point of view, the premature death of sunflowers could be explained by a trophic effect in which the high nitrogen concentration of plant tissues favours the growth of the fungus towards the conducting vessels. This can lead to an embolism phenomenon in case of strong hydric stress after flowering. The fungus has indeed been observed by microscopy inside the xylem conducting vessels at the stem base of affected plants (Seassau *et al.*, 2010b) (Fig. 6d).

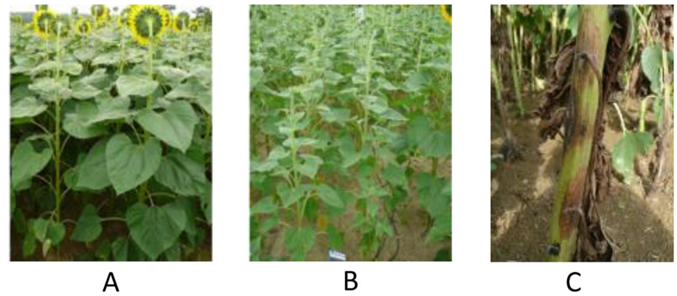

Fig. 5. Crop management and soil type have a strong impact on the development of the sunflower canopy (A and B are representing two contrasting situations). Phomopsis and phoma can compete on the stem (C): dark spots (phoma), brown lesions (phomopsis).

These results were reported in a booklet published by Terres Inovia (Bordat *et al.*, 2011) and have been integrated into the Annual Sunflower Handbook (Mestries *et al.*, 2010).

4.3.3 Verticillium wilt: an emerging fungal pathogen

Verticillium wilt (*Verticillium dahliae*) of sunflower is a soil borne disease which has long been observed in France (Alabouvette and Bremeersch, 1975). It has been increasing in recent years and is now the second most damaging disease of sunflower crops. Present in the main production areas, verticillium wilt particularly affects southwestern France

Fig. 6. Premature death due to severe Phoma black stem attacks at field level on a large area (A). The head size (B) and the root system (C) were both affected by this vascular fungus (D).

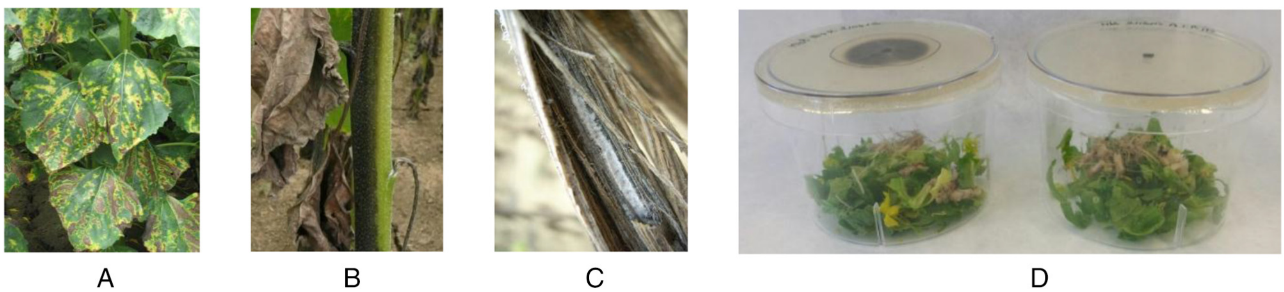

Fig. 7. Symptoms of *Verticillium dahliae* on leaf (A) and stem (B, C) of sunflower. Evaluation of the effect of brown mustard (*Brassica juncea*) decomposition on mycelium development and production of microsclerotia of the fungus (D).

(Mestries, 2017). The plant health survey carried out in 2018 by Terres Inovia and the SRAL Midi-Pyrénées in the Aquitaine and Midi-Pyrénées regions for the Bulletin de Santé du Végétal (Plant Health Bulletin) revealed that 46% of the plots visited were affected, with an average percentage of plants affected of 20%. From trials conducted by Terres Inovia, the average crop yield loss was estimated at between 2 and 3 q/ha in the South-West, but more than 50% yield losses can be observed in case of severe attacks (Mestries and Lecomte, 2012). The difficulty in controlling this pathogen comes from its telluric origin, its mode of conservation in the form of microsclerotia that can survive more than 10 years in the soil (even in the absence of a susceptible host) (Wilhem, 1955), and the quantity of primary inoculum that determines the severity of attacks (Erreguerena *et al.*, 2010). To date, no fungicide has been released against this disease and the effects of crop management on disease expression are poorly characterized or even contradictory. The lengthening of the rotation appears insufficient to reduce the risk of attack (Davis *et al.*, 1996). The only method of control is based on varietal resistance (Mestries, 2013); however, the circumvention of varietal resistance is increasingly observed.

The "Verticillium" CasDAR project led by Terres Inovia in partnership with GEVES and six seed companies aimed to assess the harmfulness of the disease and to develop a protocol for evaluating varieties in the field for breeders and for the registration of varieties in the French Catalogue (Bret-Mestries *et al.*, 2020). From an agronomic point of view, the CasDAR CRUCIAL project (2014–2018) aimed to assess the potential of biofumigation of Brassicaceae cover crops to reduce the inoculum reservoir of this fungus in the soil and the risks of attack on sunflowers. This potential biocidal effect of Brassicaceae by allelopathy and/or biofumigation is possible through the synthesis of isothiocyanates, molecules resulting from the degradation of glucosinolates (GSL) contained in their tissues (Kirkegaard *et al.*, 1998, Kirkegaard and Sarwar, 1999; Motisi *et al.*, 2013). However, the effectiveness of biofumigation requires very specific conditions: choice of species (different GSL profiles and contents), biomass produced, speed of burial, etc. In the laboratory, common turnip, forage radish and brown mustard have shown interesting potential by significantly reducing the growth of the fungus' mycelium and the germination of its microsclerotia (Fig. 7d) (Seassau *et al.*, 2016). In the field, the introduction of these species as cover crops followed by biofumigation tends to reduce the intensity and severity of attacks compared to bare soil before cultivation (Debaeke *et al.*, 2017a; Couëdel *et al.*, 2020), resulting in a yield gain of 18 to 32% (thesis of Neïla Aït-Kaci-Ahmed, in progress).

4.3.4 Three complementary modelling approaches for the control of sunflower diseases

Several modelling approaches have been initiated in order to contribute to the control of fungal pathogens through cropping system strategies (including varietal choice) (Mestries *et al.*, 2015; Aubertot *et al.*, 2016, 2018).

The first modelling approach implemented concerns the analysis of yield losses caused by the various sunflower pathogens. To this end, a first version of the SUNFLOWER-PEST pest model was developed using the X-PEST online modelling platform (developed within the framework of the European PURE project). Once the different pest functions have been integrated into the model, it will allow a diagnosis of the relative importance of the different sunflower pathogens in different production situations.

The second modelling axis concerns the integration of pathogens (phomopsis, phoma) into the SUNFLO crop model, which so far only takes into account the effects of abiotic stresses in yield build-up. This integration is deep because canopy management modifies fungal epidemics (spread, infection) *via* the microclimate (Desanlis *et al.*, 2013) then the development of symptoms on leaves and stems affects biomass and yield production. This modelling approach is promising for helping to design sunflower-based cropping systems and/or ideotypes to control one or even several interacting pathogens. Nevertheless, one of the limitations of the approach is the need for detailed knowledge and data on both the epidemiology of the diseases under consideration and the associated damage mechanisms. It will take several years to integrate all major diseases into the SUNFLO crop model in this way.

The third modeling axis aims to complete the previous one by mobilizing an innovative modeling method using published expertise and knowledge. A qualitative modelling platform (IPSIM, Injury Profile SIMulator) has recently been developed to allow the smart development of models representing a set of pests on a given crop in a given production situation (Aubertot and Robin, 2013). One of the advantages of the method is the hybridization of knowledge sources: expertise, analysis of scientific and technical literature, data sets and quantitative simulation models, when available. Different modules have already been developed or are under development on phoma (stem and collar symptoms), phomopsis, verticillium, broomrape, downy mildew and sclerotinia. The thesis of M.A Vedy-Zecchini (2020) has allowed some progress on the development of IPSIM for several pests and of the SimMat model for the easier prediction of phomopsis and phoma spore projections (Vedy-Zecchini *et al.*, submitted).

In addition to experimental approaches in greenhouses or fields, and diagnosis in agricultural plots, these modelling activities contribute to structuring research and development actions on the agroecological protection of sunflowers.

4.4 Better understand and predict grain quality

At the cooperative level, the oil concentration (whether linoleic or oleic varieties) is valued above a commercial standard set at 44%; the price supplement is most often distributed among the producers who contributed to the improved grain collection but, in some cases, only the individual performance is rewarded. However, in the absence of a simple and reliable measurement of oil concentration at the time of delivery, it is difficult to assess the variability of oil concentration between producers and fields in the collection area.

While the oil yield is quite high (~ 1.1 t/ha in average), there is still a high inter-annual variability in oil concentration at the national level (43–47% in recent years). Moreover, thanks to an extensive agronomic survey over two production basins in southwestern France (Haute-Garonne, Gers) during 3 years (2007–2009), covering two genotypes with contrasting potential oil concentration (Champolivier *et al.*, 2011b), it appeared that the variability related to the environment and crop management was much higher (approximately 10 oil points) than the one related to the variety (5 oil points). Thus

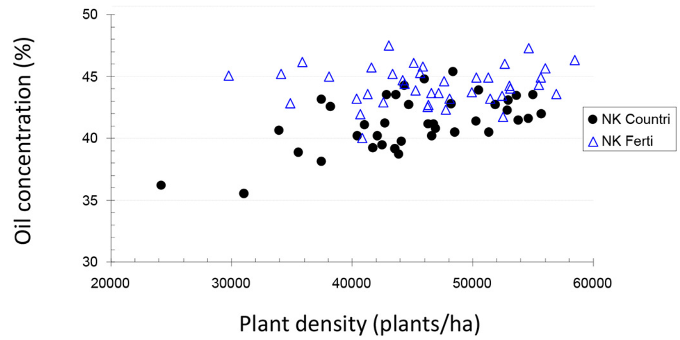

Fig. 8. Relationship between oil concentration and stand density in 2009 for two cultivars (NK Countri and NK Ferti) differing by their potential oil concentration (Champolivier *et al.*, 2011b).

knowing the oil potential of a variety is not enough to predict its performance in a given environment; crop management is also an effective lever that can be further exploited (Champolivier *et al.*, 2012). Furthermore, it was shown that stand density and regularity play an important role in oil concentration at harvest, with differences between varieties (Fig. 8). One of the unsuspected causes of the low oil concentrations at the basin scale was related to the high proportion of plots with low stand density (< 45 000 plants/ha).

Predicting the oil concentration at the plot and collection area level would improve the choice of varieties and crop management practices according to the environment. Similarly, during the season, early knowledge of the expected quality of harvest would facilitate the silo management for the cooperative.

However, this prediction comes up against the diversity of agronomic, genetic and environmental factors that interact (Andrianasolo *et al.*, 2016a). As a result, in 2011 there was no oil concentration forecasting model for sunflower encompassing all this complexity. It is with this objective in mind that the thesis of F. Andrianasolo (2014) was decided in order to better understand and model the development of the oil (and protein) concentration of sunflower seeds (achenes). As we did not have satisfactory models for this prediction, we conducted a dual approach based on both statistical and dynamic modelling.

Based on a multi-annual and multi-local database (400 cropping situations), resulting from the pooling of INRA and Terres Inovia data, several statistical models were constructed and compared (Andrianasolo *et al.*, 2014). Thus, final oil concentration was predicted from the knowledge of the variety and the duration of leaf surface after flowering with an average error of 1.9 to 2.5 oil points depending on the models. Other variables are also to be considered such as water availability (before and after flowering), nitrogen status at flowering, high temperatures during grain filling, and plant density, all affecting the functioning of carbon and nitrogen "sources" (leaves, receptacles, stems), the building of carbon and nitrogen storage "sinks" (hulls, kernels) or the source-sink relationships. This statistical model was later implemented in SUNFLO.

To build and evaluate a more mechanistic model of carbon and nitrogen accumulation, experiments were conducted in the field in Auzeville in 2011 and 2012 under contrasting cropping conditions (2 genotypes, 2 nitrogen conditions, 2 stand densities) (Andrianasolo *et al.*, 2016b, 2017). This work confirmed the strong correlation between the duration of photosynthetic activity (allowed by nitrogen nutrition) and the amount of oil per unit area accumulated during grain filling. In addition, achene protein concentration was related to the nitrogen status of the plants at flowering, nitrogen uptake after flowering and leaf area duration. The chronology of mobilization of carbon and nitrogen reserves during achene formation was genotype-dependent while the C and N dynamics involved in the variation of sizes of the sources and sinks were under the dependence of crop management (N fertilization, plant density). We also demonstrated a more pronounced susceptibility of photosynthetic activity to soil water deficit during the reproductive phase than during the vegetative one (Andrianasolo *et al.*, 2016c).

This knowledge made it possible to propose a dynamic model simulating daily oil and protein accumulation, as well as aboveground biomass during grain filling (Andrianasolo *et al.*, 2016d). While the trends were well reproduced, this model still needs to be improved to reduce the discrepancy with the observations. Nevertheless, it offers encouraging prospects for the prediction of all achene components in a multi-product rationale.

Work has continued in two directions:
- modelling the development of oleic acid concentration for a range of varieties and thermal regimes after flowering (Bachelier *et al.*, 2018);
- assessment of the variability of the dehulling ability of sunflower achenes as related to variety, management and environment, for improving the composition of oilcake for animal feed (protein content) as a result of the crushing process (Dauguet *et al.*, 2015).

4.5 Upscaling crop survey to develop operational tools for cooperatives

For a long time, agronomists have favoured the individual plot and the representative field network scales for diagnosis and agricultural advices, partly because of methodological and practical difficulties that limited the transition to the territorial dimension by simply extending the rather cumbersome methods of agronomic diagnosis.

In recent years, data from aerial (UAVs) and space (satellites) sensors for continuous crop observation have been increasing in number, their quality and accuracy are improving and their costs are decreasing. In particular, remote sensing from space makes it possible to observe large areas regularly by generating homogeneous information that is comparable between sites and dates of images. Before 2015, only the temporal series from satellites Spot, Landsat, Formosat and Deimos were used in agriculture. Since 2015, the Sentinel-1 (radar sensors) and 2 (optical sensors) are operational for more than 20 years. Their strong points are (i) temporal repeatability, (ii) spatial resolution, which is largely sufficient for monitoring agricultural plots and their intra-plot variability, and (iii) spectral richness and complementarity. Since 2015, they offer a revisit frequency of 5 days and a spatial resolution of 10/20 m, making it possible to envisage numerous agronomic applications at both plot and territorial scales (Defourny *et al.*, 2019).

Although the software and servers to manage and process this huge mass of information are more readily available, transforming reflectance data into useful and operational information and services remains a complex activity that requires complementary skills (agronomy, signal processing, computing, modelling, etc.). Combining skills in agronomy and signal processing within the same UMT has gradually become essential, the development of agronomic applications for remote sensing being an important objective for CESBio. Sunflower as a rainfed summer crop with highly variable growth patterns, has proved to be a good methodological support for this collaboration (Claverie *et al.*, 2012).

Within the "Sunflower" UMT, CESBio's research activities with remote sensing initially concerned end-of-season assessments *i.e.* better understanding of the factors limiting growth and yield according to soil types, practices and weather conditions (Dejoux *et al.*, 2010; Champolivier *et al.*, 2011b). Then, in the CasDAR project "Sunflower yield and quality forecasting" (2014–2016), in partnership with 2 cooperatives in the South-West of France (Arterris, Val de Gascogne), the challenge was to provide three types of information 4 to 6 weeks before harvest (from mid- to late July in practice), at a plot level that would allow different territorial aggregations: silo, supply area of an agricultural cooperative, and administrative scale (Champolivier *et al.*, 2019):
- mapping of sunflower-sown fields;
- earliness/lateness of the plant emergence at plot (or even sub-plot) level;
- green leaf area index dynamics of each plot which, assimilated in different types of models, should allow a better prediction of yield and oil concentration.

Indeed, forecasting harvest yield is of great interest to economic operators for questions of logistics (reduction of storage costs), management of batches in preparation for marketing and access to markets (oil and oleic acid concentration) (Champolivier *et al.*, 2011b, 2019). It must be available at the latest a fortnight before the harvest, but having the first elements available earlier, as soon as the end of grain growth, would also be valuable. In addition, aid in the decision to fertilize, irrigate or spray (fungicide) can be based on a good characterization of the leaf area index in sunflowers at key moments in the cycle.

In order to address questions relating to the mapping of sunflower areas and the earliness of plant emergence at field level, a fine analysis of optical and radar signals was carried out on agricultural plots from South-West. Sunflower crop was found to have quite different spectral and temporal responses from other crops (Veloso *et al.*, 2017). Very encouraging results of early classification of sunflower areas and plots were obtained with supervised classification methods: nearly 70% of the pixels were well classified at the end of June (Inglada *et al.*, 2016; Marais-Sicre *et al.*, 2016), and even 90% in recent works.

We were thus able to propose models for yield and oil concentration prediction based on statistical approaches exploiting Sentinel 2 satellite information in terms of active leaf area index evolution after flowering, based on the monitoring between 2014 and 2016 of 300 sunflower-sown plots (Micheneau *et al.*, 2018; Champolivier *et al.*, 2019; Attia *et al.*, 2020) (Fig. 9). We also explored the intra-plot variability

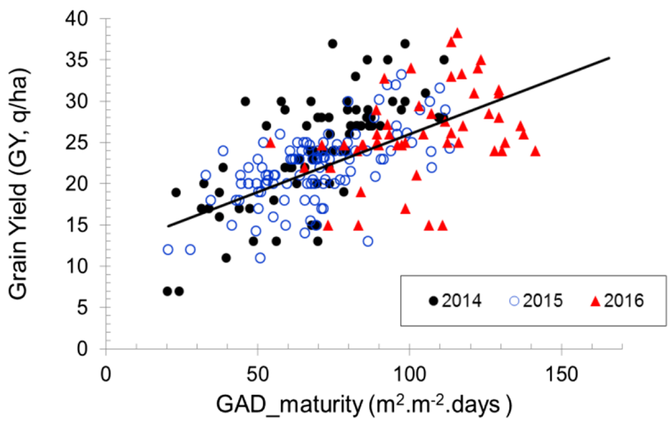

Fig. 9. Relationship between observed yield (GY, q/ha) and leaf area duration (from flowering to maturity) (GAD, $m^2.m^{-2}$.days), calculated from the interpretation of satellite reflectance data.

of leaf area index values and its dynamic evolution for the purposes of growth path typology and diagnosis of limiting factors (poor emergence, end-of-cycle diseases, drought).

The PROMISES project supported by Carnot Plant2Pro consolidates these methodological bases with a view to developing a decision support tool for irrigation and nitrogen fertilization and providing quantity and quality collection forecasts. The originality of the approach is based on this combination of models and data observed by satellite to make a prediction not only at the scale of the agricultural plot, but also at the scale of the farm and the collection basin. This tool should be connectable to the technical-economic databases of cooperatives to benefit from the information provided by farmers.

5 Assessment of this collaboration

The results of this research are numerous and have been promoted through a wide range of media: co-authored scientific publications (~25 articles and book chapters), theses (4 co-funded by Terres Inovia, 1 CIFRE grant), prototypes of decision support tools (COLLECTO, VARIETO...), articles in the agricultural press, communications in technical symposiums organized by the UMT and INRA (CIAG 2008, CIAG 2011, Sunflower Exchange Days 2016...), communications during international conferences on sunflower, organized by the International Sunflower Association (Cordoba 2008, Mar del Plata 2012, Edirne 2016, Novi Sad 2020).

The genesis of the research questions took place in a concerted manner between the partners. A "good question" for the UMT consists, over a period of 5 years, in producing the essential and useful knowledge to develop a new cultural practice, a crop management system, an innovative decision rule, or a prototype of decision support tool. The previous examples have illustrated several facets of such questions expressing this "UMT" label:

- co-construction of a simulation model that can be parameterized and manipulated by Terres Inovia engineers to carry out virtual experimentations before launching an experimental program or to carry out end-of-season assessments based on a greater variability of situations; for example, by exploring the response of grain yield to several irrigation strategies (Champolivier *et al.*, 2011a);
- joint exploration of supra-field scales, unfamiliar to both partners (grain collection area, national territory, etc.) and emerging methods (remote sensing) for agronomic diagnosis and yield forecasting;
- increased value of the partners' data sets (surveys of agricultural practices, seed quality survey, varietal and N-fertilization trials...) through modelling; for instance, data from INRA and Terres Inovia were gathered for establishing a specific critical N dilution curve for sunflower (Debaeke *et al.*, 2012d);
- revision of decision rules for crop management (*e.g.* optimal sowing density);
- production of knowledge on poorly documented diseases (*e.g.* verticillium wilt) or complex interactions between genotype, environment and crop management.

The complementary nature of the work scales issuing from this partnership has made it possible to build knowledge ranging from the plant (on the Heliaphen platform or in greenhouses) to the territory (with satellite imagery), and associating both on-farm and station experiments.

The pooling of the technical resources and skills of the UMT's partners has expanded over time and has resulted in interactions between disciplines both on research issues (*e.g.* yield prediction on the scale of the grain collection basin by joint use of remote sensing and agronomic modelling) and at the interface between research and development (*e.g.* co-construction of the recommendation on stand density, yield gap analysis). Thus, the use of the model for numerical experiments has been introduced with the aim of improving the advice on population density within a working group associating the different research and advisory competencies. By the way, the coherence between the results obtained by modelling, the knowledge acquired through experimentation and the expertise of development engineers was underlined, reinforcing the interest of the SUNFLO tool for advisers and making it possible to revise the technical position as explained in Section 4.2.

6 Perspectives

In June 2016, concluding this 10-year partnership cycle, the Sunflower Exchange Days in Auzeville brought together 130 actors of sunflower research and development, from breeding, production and processing sectors (Mestries and Debaeke, 2016). They were preceded by a consultation of a panel of partners to identify new research demands that were debated during these two days. A set of concerns emerged for the future of sunflower growing, some of which being more related to development actions (production of references, consultancy, advisory systems, etc.), others requiring research operations.

In the field of selection, the needs expressed concerned the following points:

- beyond the potential yield, it is necessary to consider the stability and regularity of the yield. One of the key points is faster and more efficient crop establishment, using varieties that are more vigorous at the start (*e.g.* three-way hybrids),

with good rooting capacity even in cold conditions and simplified tillage. The tolerance to abiotic stresses ("resilience" of varieties to climatic accidents) should also be more explicitly considered. The criteria of plant architecture (optimal leaf area, inclination of the flower head) and "quality of the maturity phase" (*i.e.* synchronization between the maturity of the receptacle and the grains) were mentioned. Another key point concerns tolerance to biotic stresses, particularly to cope with emerging problems in France such as verticillium wilt and broomrape, while not neglecting the control of other diseases (particularly mildew). Beyond these specific points, it is also a question of selecting different varieties for different environments and building coherent combinations between variety and crop management by enhancing G × E × M interactions;
- in terms of outlets, the protein content on de-oiled dry matter has been pointed out as a priority today, as sufficient efforts have already been made for oil concentration (Vear, 2016);
- upstream, the need to explore more genetic diversity (and to have tools for phenotyping genetic resources) to optimize yield stability and diversity of uses emerged as a major point, associated with the need for new operational selection methods (*e.g.* genomic selection) to increase the overall efficiency of the breeding process.

Regarding production, the main needs relate to:
- the place of sunflowers in cropping systems and adaptation of crop management, in particular by continuing work on the design and evaluation of cropping systems in the different regions of oilseed production, by using modelling to develop decision-making tools to answer the following questions: what is the best previous crop for sunflower? What influence do cover crops and soil tillage have on sunflower establishment and early growth? How can the best combination of variety × environment × management be chosen? Which suitable cropping system for which region? This research should be accompanied by the development of technical and economic reference systems that take into account market outlets;
- knowledge of the biology and/or ethology of animal pests (soil insects, birds, etc.) and soil fungi with a view to controlling them using non-chemical techniques (repellents, biofumigation, service plants, etc.).

Finally, the essential points that emerged for downstream activities are the following:
- the need for research and development on industrial processes (*e.g.* management of the variability of the contents of collected batches; "eco-friendly" processes);
- the need for research on new food outlets for sunflower oil (fatty acid profiles) and non-food outlets for by-products;
- on proteins, it appears necessary to address the following questions: how to control the protein content of the whole collection of a cooperative? What are the options on the breeding side, is there any exploitable genetic variability? What are the sources of variation (management, environment) of the protein concentration? The prediction of the hulling ability is also important;
- industry also needs methods for analysing the quality of the products (upstream and downstream);
- from a socio-economic point of view, the contribution of outlets to the profitability of the seed production must be assessed and a more refined organization must be set up along the value chain for quality control. The need for market management tools is also expressed.

Thus, new lines of force have been drawn to consolidate the partnership between research and the oil-protein crop sector:
- an extension of the UMT's scope to include other oil-protein crops and grain legumes, especially soybean and chickpea, with an application of methodological results obtained in sunflower;
- a general theme relating to the evaluation of the ecosystem services provided by the oil-protein crops and the optimization of their insertion in cropping systems, in a context of water resource limitation and adaptation to climate change;
- greater integration of new (digital) technologies for crop management and yield and quality forecasting;
- a combination of micro-economics approaches (maximization of the margin at the crop and cropping system level) and economics of innovation in commodity chains (for instance, impact of decision support tools on advisor-producer relations, payment of quality) in order to include more explicitly the establishment of grain quality in a "value chain" approach, from production to end-use.

However, the achievements of the "Sunflower" UMT still need to be strengthened and enhanced: improvements to the SUNFLO model, implementation of the model-assisted varietal evaluation approach (as an outcome of the CasDAR CARAVAGE project), development of decision support systems from ongoing projects based on modelling and remote sensing (irrigation, integrated crop protection, N fertilization, yield and quality grain forecasting), with an integration as a "Pack Advice" over the entire crop management system for interesting the cooperatives.

Topics worked on for sunflower appear to be of equal importance for soybean and chickpea. Among them are the characterization of the responses of varieties to water stress (whether in the field or on a platform), the construction of a parsimonious crop model, the analysis and exploitation of G by E by M interactions, the development of grain quality, and more useful knowledge on biotic stresses.

The issue of bird damage, which is crucial today for maintaining sunflower cultivation in most territories (Robert, 2014), requires research skills and partnerships beyond the Toulouse consortium.

Glossary

ACTA	Association de Coordination Technique Agricole
ANR	Agence Nationale pour la Recherche
CASDAR	Compte d'Affectation Spéciale « Développement Agricole et Rural » (grants from French Ministry of Agriculture)

CESBIO	Centre d'Études Spatiales de la BIOsphère, CNRS-Université Paul Sabatier (Toulouse III)
CETIOM	Centre technique interprofessionnel des oléagineux et du chanvre
CNRS	Centre National de la Recherche Scientifique
CTPS	Comité Technique Permanent de la Sélection végétale
DGER	Direction Générale de l'Enseignement et de la Recherche (from French Ministry of Agriculture)
ESAP	École Supérieure d'Agriculture de Purpan (now École d'Ingénieurs de Purpan)
ENSAT	École Nationale Supérieure d'Agronomie de Toulouse
GEVES	Groupe d'Éude et de contrôle des Variétés Et des Semences
GIS GCHP2E	Groupement d'Intérêt Scientifique Grandes Cultures à Hautes Performances Economiques et Environnementales
INP	Institut National Polytechnique (Toulouse)
ISA	International Sunflower Association
LIPM	Laboratoire des Interactions Plantes-Micro-organismes, INRA-CNRS
MAAF	Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt
OAD	Outil d'aide à la décision
ONIDOL	Organisation nationale interprofessionnelle des graines et fruits oléagineux
Plateforme RECORD	Plateforme pour la modélisation et la simulation informatique des agro-écosystèmes
PROMOSOL	Association pour la promotion de la sélection des plantes oléagineuses
RMT	Réseau Mixte Technologique
SIDO	Société Interprofessionnelle des Oléagineux
SRAL	Service Régional de l'Alimentation (Ministère de l'Agriculture)
UMR AGIR	Unité Mixte de Recherche AGroécologie-Innovations-Territories, INP-ENSAT, INP PURPAN, ENSFEA
UMT	Unité Mixte Technologique
UMT CAPTE	UMT « Capteurs et Télédétection pour caractériser l'état et le fonctionnement des grandes cultures »
UPS	Université Paul Sabatier (Toulouse III)

Supplementary Material

French Version
L'agronomie du tournesol : 10 années de recherche en partenariat dans l'UMT Tournesol à Toulouse.

The Supplementary Material is available at https://www.ocl-journal.org/10.1051/ocl/2020006/olm.

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