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Opportunities and risks of double cropping in southwestern France with a focus on soybean and sunflower crops☆

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Abstract – Growing a second food, fodder or bioenergy crop during the fallow period commonly refers to sequential double cropping or relay cropping practices, as a function of sowing date (following or within the primary crop, respectively). Such practice may generate an additional income while supplying support and regulation services. As such, it could be referred as a form of ecologically intensive agriculture but also an opportunity offered by climate change. The decision-making process in the adoption of double cropping relies on many factors related to soil and climate conditions, but also on profit expectation and risk perception. The CASDAR project "3C2A: Three crops in two years" (2019–2023) strived to create references for sequential double cropping in the South-West of France, which encompasses the regions of Nouvelle-Aquitaine and Occitanie. The project focused mainly on grain crops and raised the interest of the use of oil-protein crops such as soybean (*Glycine max* (L.) Merrill) and sunflower (*Helianthus annuus* L.) for such practice. As a preliminary contribution of 3C2A project, this paper aims at illustrating the potential interest of soybean and sunflower as double crops in the South-West of France through a qualitative analysis of farmers' perceptions about the risks and opportunities of double-cropping completed by a 4-years on-farm evaluation of agronomic and economic performances of this practice (110 fields).

Keywords: yield / net income / climate change / irrigation

Résumé – Opportunités et risques de la double culture dans le Sud-Ouest de la France avec un focus sur les cultures de soja et de tournesol. La pratique d'une deuxième production (alimentation humaine ou animale, bioénergie) pendant la période d'interculture se réfère à ce que l'on nomme la culture dérobée ou la culture en relais selon la date de semis (après ou au sein de la culture primaire). Cette pratique peut générer un revenu supplémentaire tout en fournissant des services de soutien et de régulation. En tant que telle, elle peut être considérée comme une forme d'agriculture écologiquement intensive, mais aussi comme une opportunité offerte par le changement climatique. Le processus de prise de décision concernant l'adoption de la double culture repose sur de nombreux facteurs liés aux conditions pédologiques et climatiques, mais aussi sur l'espérance de gain et la perception du risque. Le projet CASDAR « 3C2A : Trois cultures en deux ans » (2019–2023) s'est efforcé de créer des références utiles pour la double culture dans le Sud-Ouest de la France, englobant les régions Nouvelle-Aquitaine et Occitanie. Le projet s'est principalement concentré sur les cultures à graines et a soulevé l'intérêt d'insérer des oléoprotéagineux tels que le soja (*Glycine max* (L). Merrill) et le tournesol (*Helianthus annuus* L.). En tant que contribution préliminaire au projet 3C2A, cet article vise à illustrer l'intérêt potentiel du soja et du tournesol en tant que doubles cultures dans le Sud-Ouest de la France par une analyse qualitative des perceptions des agriculteurs sur les risques et les opportunités de cette pratique, complétée par une évaluation sur 4 ans des performances agronomiques et économiques de cette pratique chez les agriculteurs (110 parcelles).

Mots clés : rendement / revenu net / changement climatique / irrigation

☆ Contribution to the Topical Issue "Innovative Cropping Systems / Systèmes innovants de culture".
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Highlights

- Farmers have both economic and agronomic motivations for double cropping.
- Soybean appears to be more profitable than the other crops tested as double crops.
- Securing water requirement is a key factor of success of summer double cropping in South-West region.
- Irrigation costs can be compensated by high selling prices.

1 Introduction

Global warming, soil degradation and natural resource depletion all threaten crop productivity and environmental sustainability of agriculture. In addition to the agricultural prices volatility, this urges the transition to more sustainable systems such as "ecologically intensive agriculture" or more resilient and "biodiversity-based" farming systems which could help (re)-generate ecosystem services and limit negative agricultural impacts (Bonny, 2010; Ghali *et al.*, 2014; Tittonell, 2014). This requires an increase in cultivated biodiversity at field, farm and landscape scales, which could be achieved, for instance, through crop diversification in space and time (Lithourgidis *et al.*, 2011; Duru *et al.*, 2015). To do so, an option could be to grow an additional cover or cash crop during a fallow period. This would increase land use efficiency and, in case of cash crops, yield per unit of cropping area (Caviglia *et al.*, 2004; Heaton *et al.*, 2013; Bowles *et al.*, 2020; Liu *et al.*, 2020). Moreover, such practice may provide an additional income to the farmer while supplying support and regulation services such as (i) soil cover during fallow period which can contribute to increase soil carbon storage and reduce loss of nutrients, (ii) nitrogen symbiotic fixation by introducing legumes, or (iii) pest suppression by a break crop effect (Schipanski *et al.*, 2014; Bulan *et al.*, 2015; Blesh, 2018; Wauters *et al.*, 2021). As such, it could be referred as a form of ecologically intensive agriculture.

Cultivating a second food, fodder or bioenergy crop during fallow period commonly refers to double cropping or relay cropping practices. Double cropping consists of growing two crops sequentially on a field. In temperate and Mediterranean areas, this corresponds to a summer crop *e.g.* maize (*Zea mays* L.), soybean (*Glycine max* (L.) Merrill), sorghum (*Sorghum bicolor* (L.) Moench), or sunflower (*Helianthus annuus* L.), planted immediately after the early harvest of a winter-sown crop (*e.g.* barley (*Hordeum vulgare* L.), pea (*Pisum sativum* L.), oilseed rape (*Brassica napus* L.) (Jacquin, 1992; Yamane *et al.*, 2016). Relay-cropping is another multi-cropping practice, where a crop is planted into an already established crop, their growing periods therefore overlapping (Tanveer *et al.*, 2017; Lamichhane *et al.*, 2023) *e.g.* soybean sown at barley or wheat heading. Both practices are widely spread throughout the world but in regions with sufficient temperature and water (Zhang *et al.*, 2008; Wang *et al.*, 2012; Borchers *et al.*, 2014; Andrade and Satorre, 2015; Schnitkey, 2018; Kawasaki, 2019; Page *et al.*, 2019; Xu *et al.*, 2021; Simon-Miquel *et al.*, 2023). In addition, it has been suggested that climate change might create new opportunities for such practices in more temperate countries although this is true only if water deficit induced by high temperature and lack of precipitation could be alleviated through irrigation (Seifert and Lobell, 2015; Gammans and Mérel, 2019; Gao *et al.*, 2019; Kawasaki, 2019).

In France (and in Europe), double cropping is mostly used to produce a second fodder or bioenergy crop (Brochier *et al.*, 2011; Graß *et al.*, 2013; Morand *et al.*, 2013). Yet, autumnal soil coverage is now mandatory on lands classified as vulnerable zones according to the EU Nitrates Directive. This has led some farmers to test double cropping as an opportunistic replacement of cover crops (Callewaert, 2016). The decision-making process in the adoption of double cropping relies on many factors related to soil and climate conditions, but also profit expectation and risk perception (Shapiro *et al.*, 1992).

The CASDAR project "3C2A: Three crops in two years" (2019–2023) strived to create references for double- and relay-cropping in the South-West of France, which encompasses the regions of Nouvelle-Aquitaine and Occitanie. The project focused mainly on grain crops rather than fodder or bioenergy crops, which have been more referenced in France so far (Brochier *et al.*, 2011; Morand *et al.*, 2013). Grain crops are interesting as double crops since they can provide an additional income, diversify risk strategies, and spread-out fixed costs (Shapiro *et al.*, 1992). Nevertheless, they may require additional production costs (Borchers *et al.*, 2014) and introduce new management risks.

Oil-protein crops such as soybean and sunflower have the potential to enhance crop productivity and profitability in a wide range of cropping systems (Le Gall *et al.*, 2022). Oilseeds are inherently resilient crops that can diversify rotations based on winter cereals and have an advantage over the other crops in terms of prices, wider adoptability and relatively optimal production under environmentally stressed conditions (Reddy and Suresh, 2009). Soybean and sunflower, already grown as main crops, could be also considered as good candidates for double cropping in southwestern France, mainly due to the breeding of very-early cultivars allowing a short growing period (100–120 days) (Egli and Bruening, 2000; Lecomte, 2009; Vlachostergios *et al.*, 2021; Debaeke *et al.*, 2021). Cultivation and performances as double crops of both species have been reported in many countries (Borchers *et al.*, 2014; Andrade and Satorre, 2015; Yamane *et al.*, 2016; Hansel *et al.*, 2019). Furthermore, the sunflower and soybean sectors are well developed in southwestern France, these crops being two pillars of the cropping systems in rainfed and irrigated systems, respectively. However, very few references have been produced in Europe on the performance of these two oil-protein crops grown as double crops. In France, to our knowledge, no statistical data are available to evaluate the contribution of double crops to harvested areas or production of arable land.

As a first issue of the 3C2A project, this paper aims at illustrating the potential interest of soybean and sunflower as double crops in the South-West of France through a qualitative analysis of farmers' perceptions about the risks and opportunities of double cropping completed by the 4 years of an on-farm network intended for global evaluation of agronomic and economic crop performances.

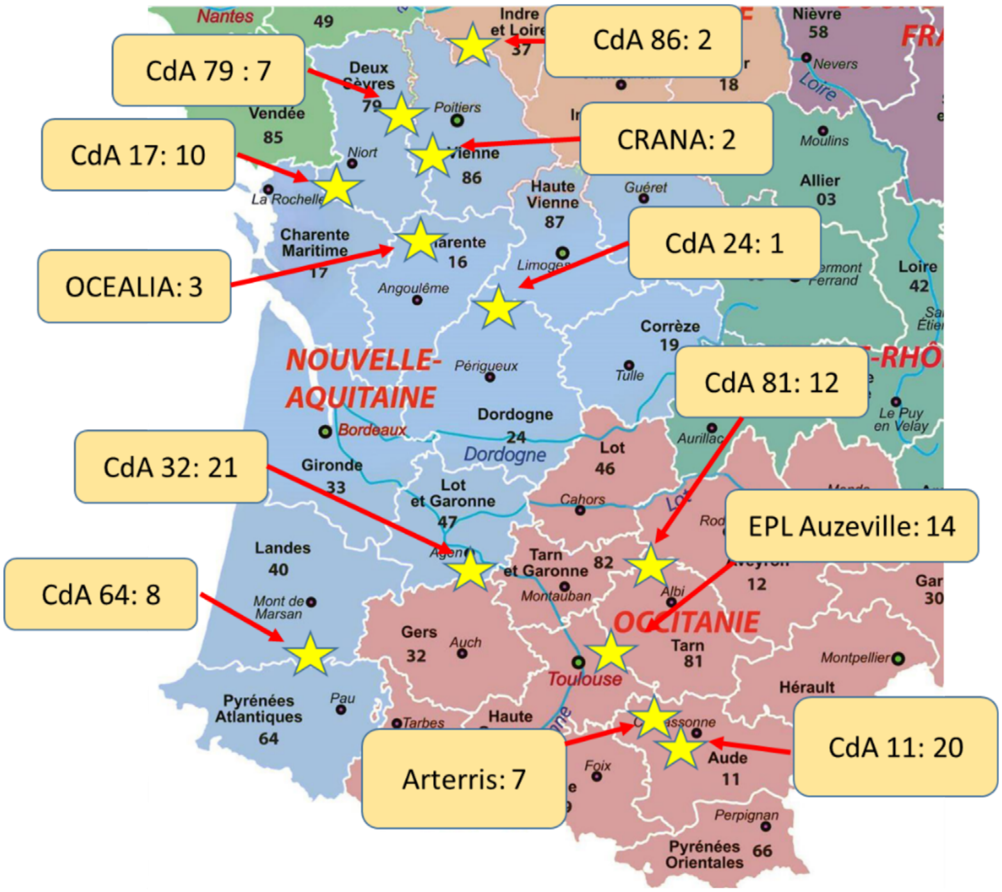

Fig. 1. Localization of the field trials (2019–2022) monitored by the 12 partners of the 3C2A project (CdA: Chambre d'Agriculture; Nouvelle-Aquitaine: 17 (Charente-Maritime); 24 (Dordogne); 64 (Pyrénées-Atlantiques); 79 (Deux-Sèvres); 86 (Vienne); Occitanie: 11 (Aude); 32 (Gers); 81 (Tarn); Cooperatives: Arterris (31 – Haute-Garonne); CRANA (86); Ocealia (16 – Charente); Training: Exploitation du Lycée Agricole de Toulouse-Auzeville (31)). 11, 16, 17, 24, 31, 32, 64, 79, 81 and 86 are the department numbers; the numbers after the colons correspond to the field numbers.

2 Materials and methods

2.1 Survey of farmer's perceptions about double cropping

Data collection was performed in 2020 and 2021 through an online survey and direct interviews. The objective was to identify the current farmer's practices (relay or double crops) in Nouvelle-Aquitaine (Charente, Charente-Maritime, Vienne, Pyrénées-Atlantiques) and Occitanie (Aude, Gers, Haute-Garonne, Hautes-Pyrénées, Tarn, Tarn-et-Garonne). The questionnaire was designed to express the farmer's motivations behind the establishment of double cropping and the main perceived factors of success and failure of these practices. The questionnaire was adapted to each type of cropping system surveyed (catch crop/relay cropping/no double cropping). Finally, 29 answers were collected online and 14 through interviews with farmers. Direct survey resulted in more accurate data on crop management. The sample of farmers surveyed included both farmers participating or not to the 3C2A project through field experimentation of double crops. Within the group, 35 farmers already had experience in double cropping, 7 had tested relay cropping, and 6 had never tested either of these practices. Fodder crops, soybean, sunflower, maize, sorghum and buckwheat (*Fagopyrum esculentum* Moench) were sown as sequential double crops, but only soybean and sorghum were tested as relay crops within wheat.

2.2 On-farm experiments

The goal of these on-farm trials was to evaluate the feasibility and performances of different crops and management systems applied to double cropping. Between 2019 and 2022, 130 double crop trials scattered throughout Nouvelle-Aquitaine (NW and South) and Occitanie (Center) regions (Fig. 1) were set up by volunteer farmers as part of the 3C2A project. Over the years, 32 and 29 fields were sown with very early varieties of soybean and sunflower respectively. Among the 130 fields, only 96 were monitored until harvest with yield measurements (from combine harvester or from manual sampling when the farmer had evaluated the harvest operations as not profitable).

In order to cope with current agricultural practices, each farmer decided by himself on the sown crop species, soil tillage, weed control (chemical or mechanical), fertilization

Table 1. Factors perceived by farmers as influencing harvest failure or success of double crops from interviews and online survey.

Factors of harvest failure	*Explanation*	Factors that help secure harvest success	*Explanation*
Water stress	Limited summer rainfall	Irrigation	To compensate for rainfall shortage
Thermal stress	Excessive summer temperatures	Early harvest of the preceding winter crop	To sow the double crop as early as possible
Weather conditions during harvesting windows	Humid conditions in October: harvest delay and grain losses	Choice of cultivar: early to very early maturity group	Cultivars that require shorter growing periods
Weed control	Cereal volunteers (competition)	Sowing the double crop less than 72 h after the winter crop's harvesting	Saves residual soil water, which is beneficial for the double crop's emergence
Persistence of pesticides	Phytotoxicity (herbicides applied on the previous crop)	Destruction of winter crop's volunteers	Limits water competition
		Having a grain drying system (preferably at farm level)	To bring forward the winter crop's harvest date and secure double crop's harvest

and irrigation. In each trial, information was received on: (1) pedoclimatic conditions, (2) cultural practices, and (3) grain yields. The causes of crop failure were recorded when this occurred. The information on the crop management of the 130 fields was also collected through interviews or on-line survey.

Socio-technical data analysis was performed using SYSTERRE®, a tool developed by Arvalis (Jouy and Tournier, 2011). It allows the calculation of production costs to assess the economic performance of field crops at plot and farm level. References from the SYSTERRE® databases were used to evaluate the components of production costs, which were not directly available from the field data. Semi-net margins (SNM) were thus evaluated as the difference between gross product (actual yield × commodity price) and production costs, calculated as the sum of applied inputs (seeds, fertilization, weed and pest control), irrigation costs and mechanical costs (soil tillage, sowing, harvest).

3 Results and discussion

3.1 Current practices in southwestern France and factors of success or failure

A first conclusion of the survey was that relay cropping was not widely represented over this territory. Only five farmers declared having tested relay cropping, three in the online survey (OS) and two in the direct survey (DS). A main explanation is that such practice is perceived as technically complicated and risky, weed control being one main difficulty to succeed (Lamichhane *et al.*, 2023). Most of the farmers were qualified as "conventional" and adopted reduced tillage or even minimum tillage (or direct seeding) when involved in conservation agriculture. Organic farmers represented 13% of the panel that was surveyed online.

The six farmers who had never tested one of the two practices perceived five main constraints in the practice of double cropping:

– time-consumption during already busy periods (harvest of winter crops, irrigation of maize crops...);
– necessity of adequate machinery (seeder...), especially for relay cropping;
– strong dependence upon irrigation to secure the practice;
– weed control problems (especially true for organic farmers and relay cropping);
– lower efficiency than cover crops for increasing soil organic matter and reducing weed seed banks.

Interviews revealed that farmers had both economic and agronomic motivations for double cropping. They aim at increasing their income per hectare, replacing cover crops in areas where autumnal soil coverage is compulsory, or compensating for poor results from the previous winter crop. They also aimed at protecting soil from water and wind erosion risks and diversifying their crop rotations. The factors perceived by the farmers as contributing to the success of double crops were outlined in Table 1. Relay-cropping was not analyzed in this paper due to the very low number of practitioners (see Lamichhane *et al.* (2023) for the analysis of success and failure of this practice). The factors that ensure harvest success or failure are quite related: success means the resolution of a technical problem that could have led to failure otherwise. Irrigation appears as a key factor to secure sufficient yield at harvest. Obviously, this may have been biased by the exceptionally dry weather experienced in July 2020 (for instance, 3 mm of rain in 2020 *vs.* 44 mm on 1994–2019 period in Toulouse) at the time of the survey (Table SI-1). Decisions related to crop duration and early maturity in autumn (through sowing date and cultivar choice) were also perceived as important factors of success especially when autumn conditions were particularly wet. On the same line, owning a grain drying system is a factor for securing the double cropping practice in case of delayed harvest.

Soybean (40% DS and 10% OS) and sunflower (20% and 13% respectively) were among the main crops used for double

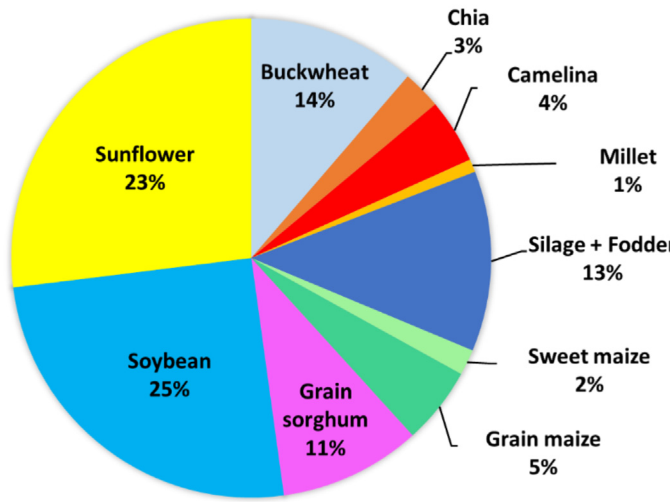

Fig. 2. Distribution of the crop species used as double crops from 2019 to 2022 in Nouvelle-Aquitaine and Occitanie according to the 130 sown fields.

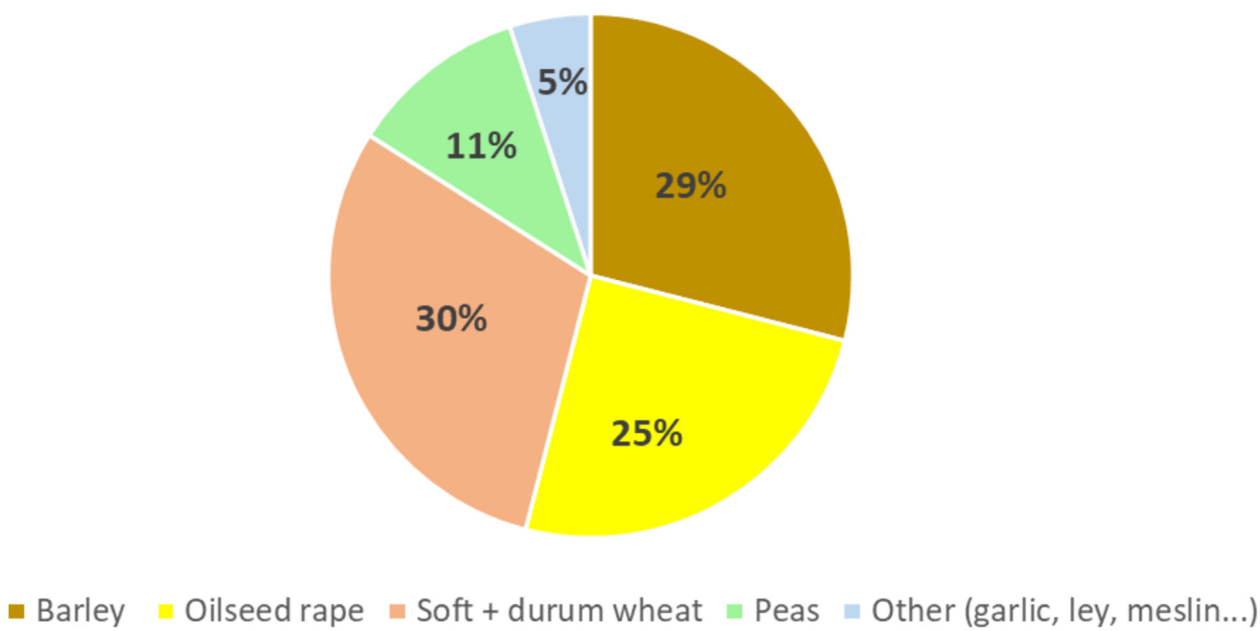

Fig. 3. Distribution of the crop species preceding the sowing of double crops from 2019 to 2022 in Nouvelle-Aquitaine and Occitanie from the agronomic survey of farmer's fields.

cropping in the region according to the 2020–2021 survey. This was confirmed by the distribution of double crops as sown by the farmers participating to the on-farm network during the 4 years (Fig. 2). According to the 130 trials, soybean and sunflower were grown in 25% and 23% of the fields respectively, followed by buckwheat (14%) and grain sorghum (11%). Other double crops (27%) were: grain maize, energy crops (including silage maize), fodder crops (including forage maize, millet (*Panicum miliaceum* L.), and various grass-legume mixtures), camelina (*Camelina sativa* (L.) Crantz.), sweet maize, and chia (*Salvia hispanica* L.). According to the 130 fields, the main previous crops were small-grain cereals (barley, soft and durum wheat), oilseed rape (for seeds or oil) and field pea (Fig. 3). Consequently, the most frequent "winter crop–summer crop" sequences were: (1) oilseed rape followed by soybean, sorghum or sunflower: 24%; (2) barley followed by soybean or maize: 20%; (3) wheat followed by soybean, sunflower or buckwheat: 19%. The most frequent practices for double cropping are (Fig. 4): mechanical operations to shred and shallowly bury the residues from previous crop (55%), no herbicide (58%) nor fertilizer (77%) applications and supplemental irrigation (54%). The absence of *N* fertilizer was related to the high contribution of soybean in the panel (25%). The soybean varieties most commonly used were ES Comandor (000), Herta PZO (000), Solena (000) and ES Mentor (00). In sunflower, very early varieties such as SY Arco

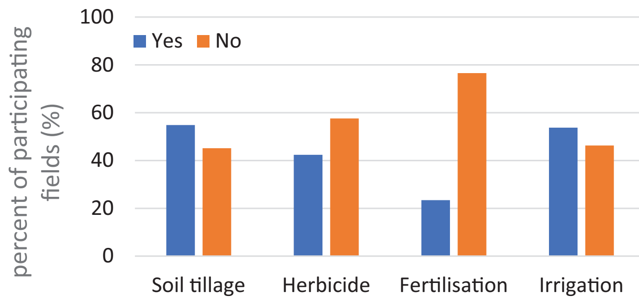

Fig. 4. Characterization of 4 cultural practices used in double crops (Yes or No, %): soil tillage, chemical weed control, fertilization, and irrigation; 2019–2022 (all crops).

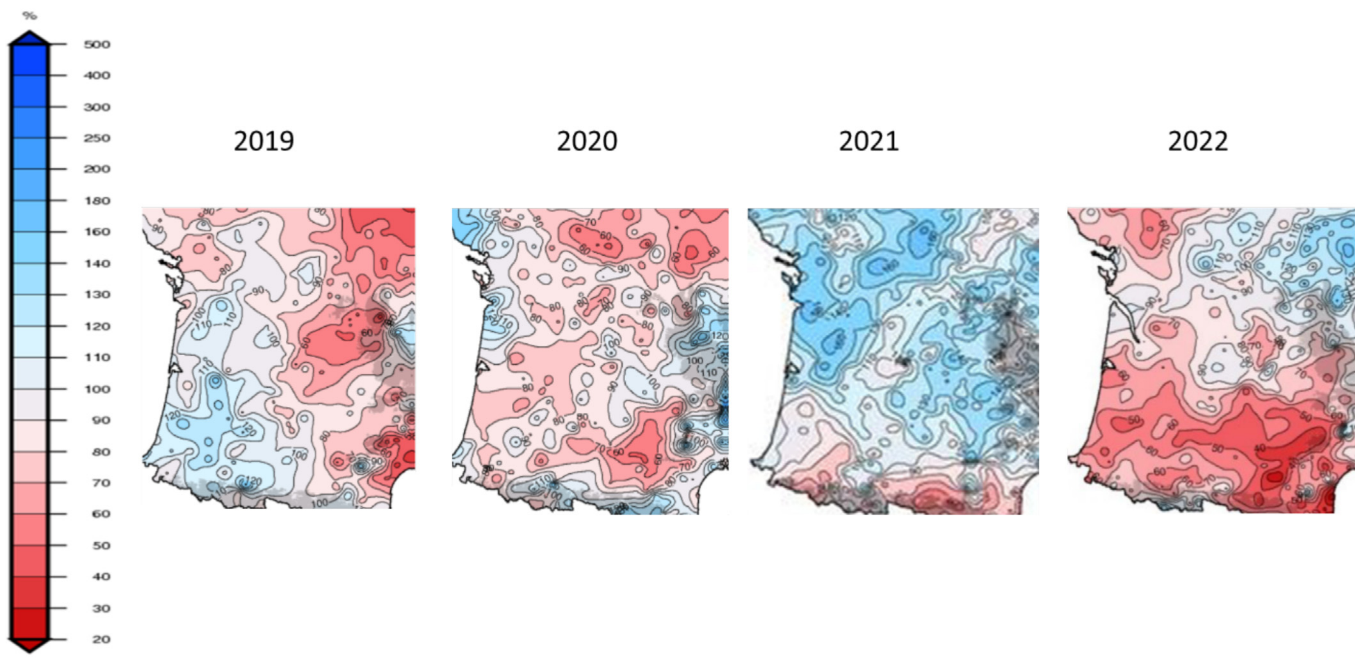

Fig. 5. Relative deviation (%) of summer precipitation (June to August) from 30 years medians for the 4 years of study (2019–2022). For 2019–2021, the 30 years reference was the median of 1981–2010 and for 2022, the reference was the median of 1991–2020 (data from Meteo France).

and ES Baltic or early varieties as MAS 82OL and Durban CS were frequently sown. Cv.Harpe was the most represented buckwheat variety. The median duration between primary crop harvest and double crop sowing was of 6 days (0–20) and the double cropping duration was of 119 days (from 77 to 160).

3.2 Agronomic and economic performances of 6 double crops

Monthly precipitation was provided on a panel of 9 weather stations throughout the two regions from June to September (2019–2022) (Table SI-1). The summers of 2019 and 2020 were not favorable for double cropping in South-West region. The low amount of rainfall after sowing delayed plant emergence and hindered crop growth. High temperatures in July and August (*e.g.* in Toulouse: 34 days with Tmax > 30 °C in 2019; 25 in 2020) with little to no rainfall (Fig. 5) dramatically impacted yields in rainfed conditions. Then from mid-October in 2019, excessive rainfall hampered crop harvests. In 2021, the late harvest of winter crops due to frequent precipitation delayed the sowing of second crops but soil moisture was optimal for the establishment of double crops. The summer of 2021 was relatively dry and more favorable in terms of temperature (*e.g.* in Toulouse: 16 days with Tmax > 30 °C) but conditions became very humid at the end of the crop season, delaying grain maturity and impairing harvest operations. The 2022 season from May to September was exceptionally dry and hot (*e.g.* in Toulouse: 40 days with Tmax > 30 °C in July and August); this resulted in very early harvesting of preceding winter crops from mid-June and thus in early sowing of double crops, which is a potential factor of success. However, irrigation amounts for securing the summer crops were extremely high for double crops.

Therefore, over the 130 plots monitored during the four years of farm trials, up to 39% were not harvested due to impairing climatic conditions with some variations according to the crop species (Fig. 6a): 21% for sunflower, 22% for

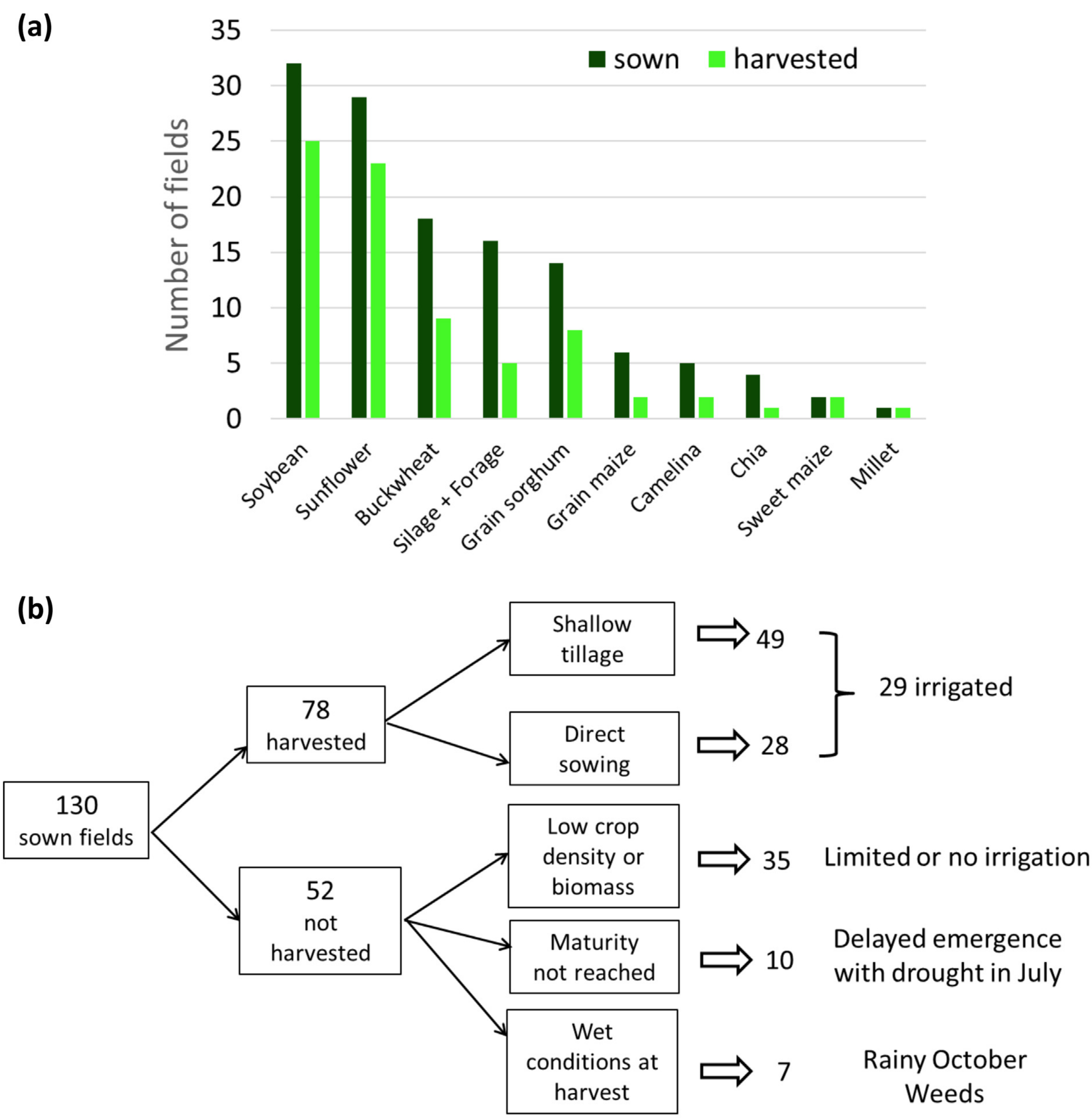

Fig. 6. Quantitative evaluation of the success and failure of sown double crops. (a) Number of sown and harvested fields for 10 types of double crops (2019–2022). (b) Clustering of the fields according to the reasons of success or failure.

soybean, 43% for sorghum and 50% for buckwheat. In some cases, crop maturity had been delayed because of summer drought, which delayed seed germination and plant establishment (Fig. 6b). In other cases, harvest was impossible because of uncontrolled weeds or too wet conditions in autumn. But most cases of crop failure were assigned to water deficit after sowing resulting in poor crop stands and reduced biomass at harvest. All types of double crops and management systems were affected by this failure. However, 52% of non irrigated crops were not harvested while only 21% of irrigated crops resulted in crop failure.

Grain yields (Fig. 7) and semi-net margins (Fig. 8) were compared for the 6 main species sown as double crops. Non-harvested fields with poor crop development were not considered for yield (67 fields) but for SNM (90 fields). The production costs were averaged over the 2019–2021 period. The selling prices were actualized each year, including 2022. Grain yield was significantly different among the 6 double crops (P-value = 9.2E-04). This was mainly explained by the low productivity of camelina and buckwheat when compared to sorghum (P-values = 0.132 and 0.019 respectively) and soybean (P-values = 0.020 and 0.027 respectively). Camelina and buckwheat were mostly grown as rainfed crops in Nouvelle-Aquitaine resulting in low yields as double crops. Grain yields were extremely reduced when less than 150 mm water was available (from precipitation and/or irrigation)

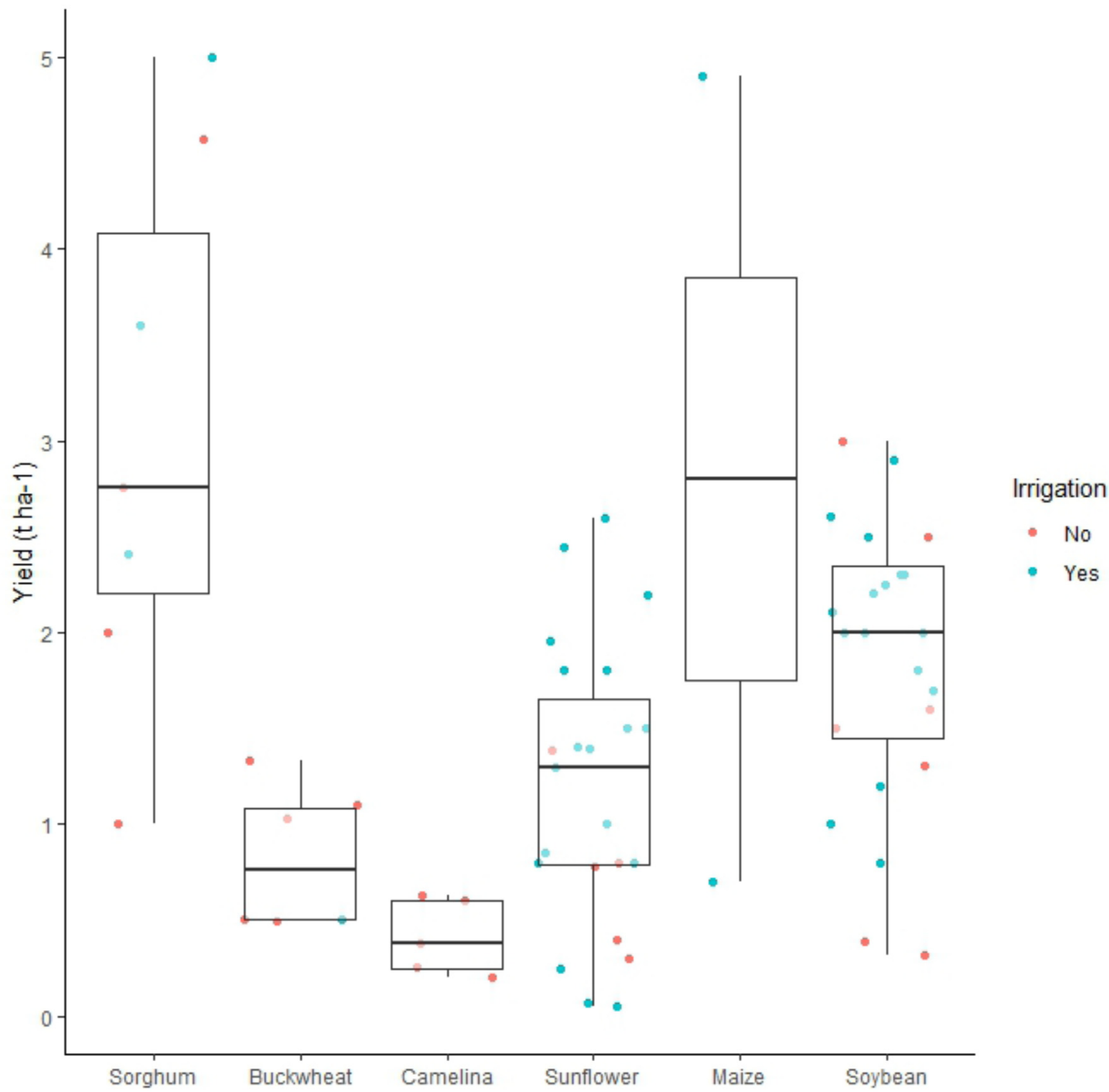

Fig. 7. Harvested grain yield (t.ha^{-1}) of 6 double-crops from on-farm trials (2019–2022); grain yields are expressed at standard moisture content from combine harvesting or hand sampling (N = 67 fields: 7 sorghum, 6 buckwheat, 5 camelina, 23 sunflower, 2 maize, 24 soybean).

between June 15 and September 15: < 1 t.ha^{-1} for soybean, sunflower or sorghum whereas up to 3, 2.6 and 5 t.ha^{-1} were attainable by these crops with enough water. As well as for the same main crops, yields of maize and sorghum were the highest among the tested double crops. Semi-net margin (SMN) including non-harvested fields was significantly different among the 6 double crops (P-value = 2E-04) (Fig. 8). This was mainly explained by the high SMN of soybean compared to sorghum (P-value = 0.002), maize (P-value = 0.008) and buckwheat (P-value = 0.011).

Buckwheat was suggested as the best candidate for double cropping in the North of Nouvelle-Aquitaine, since its growing period is shorter, and it doesn't require irrigation (Ferrand, 2018). Buckwheat growing period is very short (1060 GDD needs with a base temperature of 6 °C) and rainfed yields could be rather good (1–1.2 t.ha^{-1}) with sufficient precipitation. Buckwheat from 3C2A trials had similar semi-net margins than sunflower.

A two-factor ANOVA was performed to disentangle the effects of crop species from irrigation, as the latter was expected to have a huge impact on yield and thus on SNM. Yet, the ANOVA showed that the effects of crop, irrigation and crop × irrigation interaction on yields were all significant (P-values = 0.002, 0.001 and 0.030 respectively). However, when including the non-harvested fields, SNM was only different between crops while irrigation had a moderate but not significant effect (P-value = 0.054).

Among the crops tested in the 3C2A project, some had less promising results than soybean, sunflower and buckwheat. Sorghum seems feasible but had poor economic results due to low commodity prices (115–145 €.t^{-1} in 2019–2020; up to 290 €.t^{-1} in 2022) and low yields (2–4.5 t.ha^{-1}) as a double crop. Camelina resulted in very low to no harvest (0–0.6 t.ha^{-1}). However, the sector's demand is growing, and commodity prices can be very interesting (around 500 €.t^{-1}) compensating the low productivity of camelina. Potential

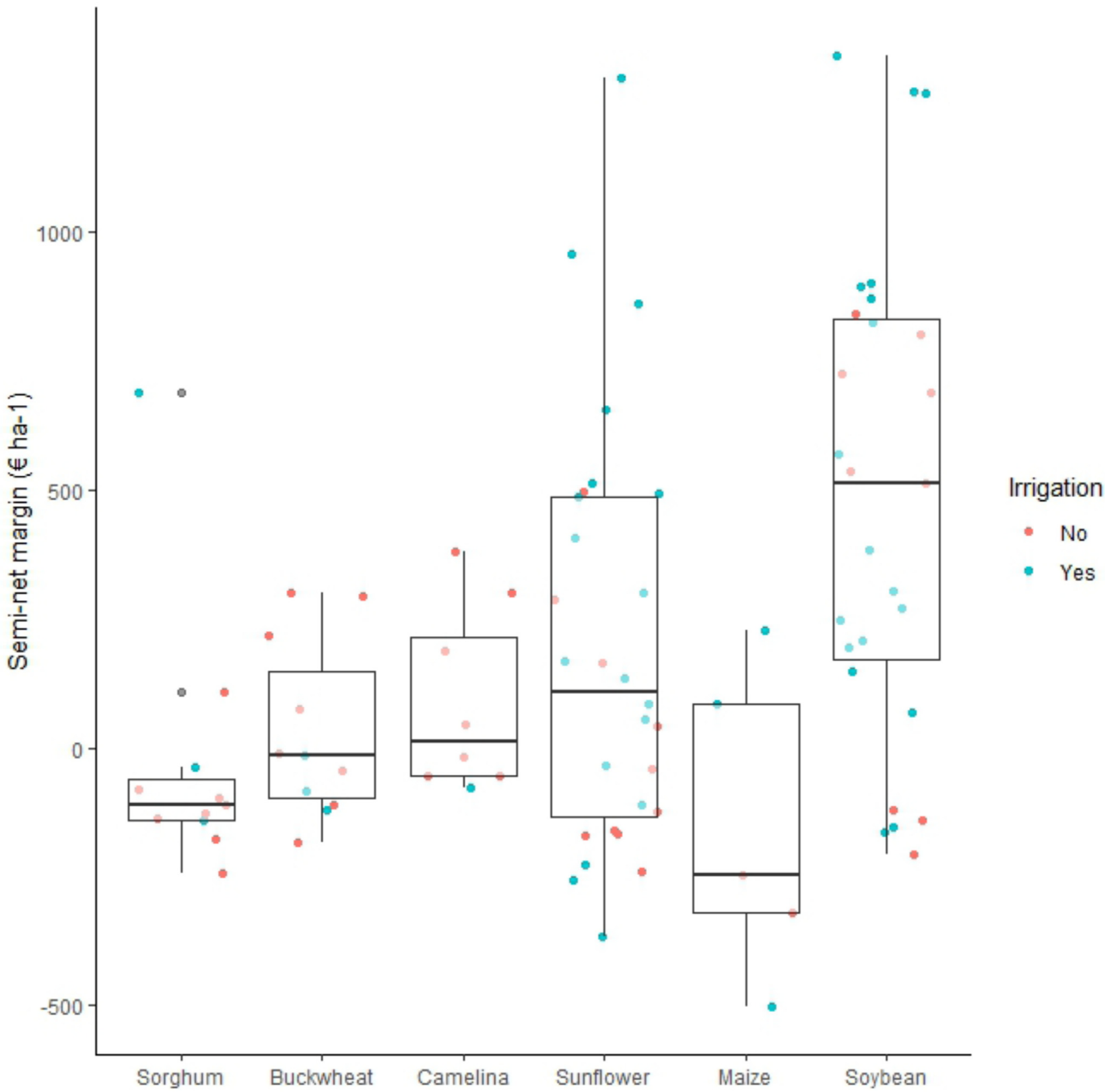

Fig. 8. Semi-net margins (€.ha^{-1}) of 6 double crops from on-farm trials in 2019–2022, including non harvested situations ($N = 90$ fields: 11 sorghum, 11 buckwheat, 8 camelina, 28 sunflower, 5 maize, 27 soybean).

yields of 2 t.ha^{-1} have been reported for camelina double crop when fully irrigated (Allard, 2021). On the other hand, yields of 1 to 2.5 t.ha^{-1} were reported when camelina was early spring-sown as a main crop while not irrigated.

3.3 Securing water requirement as a key factor of success in soybean and sunflower

As mentioned, water stress was the most obvious factor explaining crop failure. Two-thirds of the 32 soybean plots were irrigated with an average amount of 180 mm applied (128 to 193 mm according to the growing seasons). Most soybean harvests were successful (78%), and the severe failures occurred in rainfed conditions. However the trials located in the Béarn and Pays Basque region (Pyrénées-Atlantiques, SW Nouvelle-Aquitaine) receiving sufficient rainfall due to a humid microclimate, *e.g.* 109 mm on average in July and August (*vs.* 50 to 63 mm for the other weather stations in Occitanie and North of Nouvelle-Aquitaine) (Table SI-1), were not irrigated. These trials resulted in promising yields even under rainfed conditions (2.5–3 t.ha^{-1}).

In the case of sunflower double cropping (29 sown trials), all crop failures were due to lack of soil moisture in unirrigated conditions. As in soybean, two thirds of the sunflower trials were irrigated but the unirrigated conditions did not benefit from abundant precipitation systematically. The successful

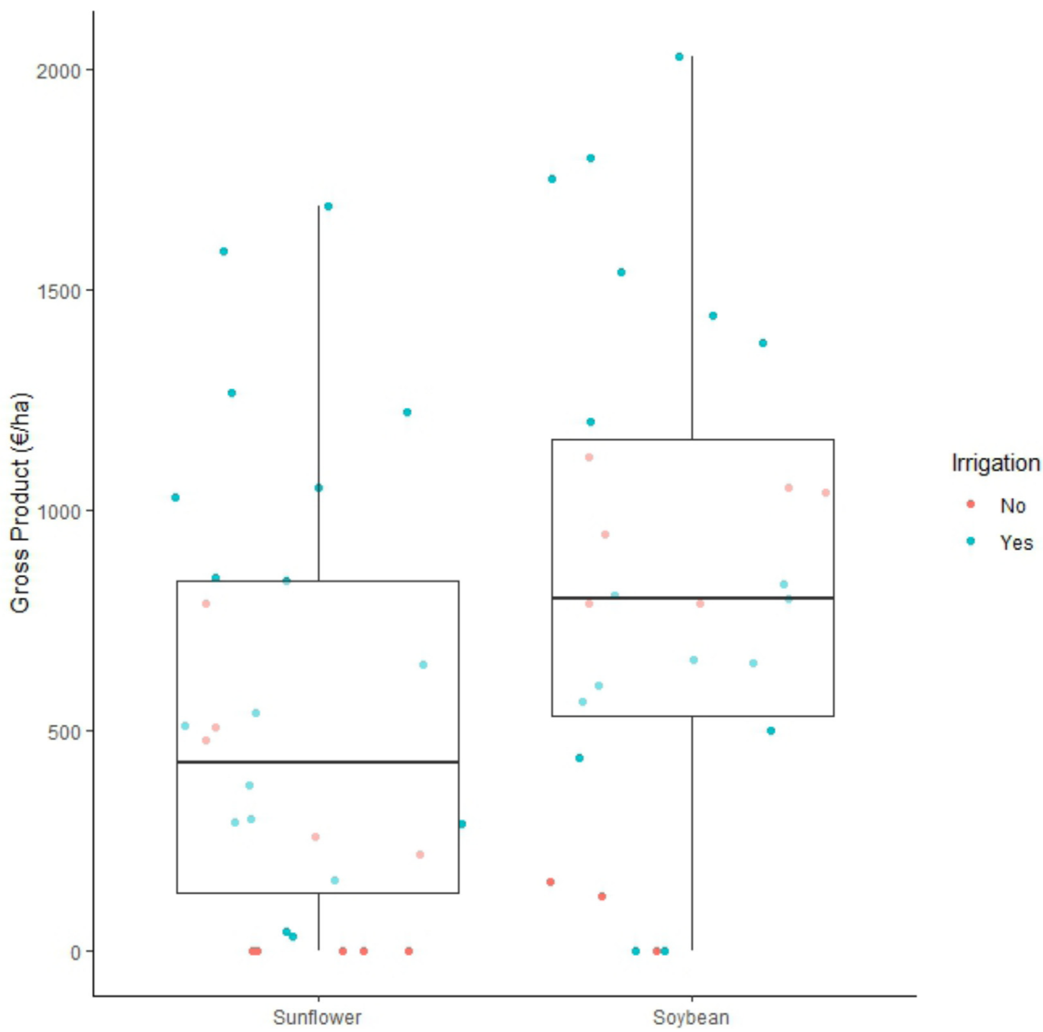

Fig. 9. Gross products (€.ha^{-1}) of sunflower and soybean grown as double crops within on-farm trials in 2019–2022 including non harvested situations (N = 55 fields: 28 sunflower, 27 soybean).

trials received at least 25 mm after sowing to secure seedling emergence and early growth. Most fields were also irrigated during flowering, to reduce water stress during the most susceptible phase and secure oil content. In 2019, 2020 and 2022, due to water shortage and high temperatures, the average irrigation amount was 80–90 mm. In 2021, 48 mm were applied to sunflower, as the summer season was more rainy and cooler. However, even when water requirements were satisfied, 6 trials out of 18 resulted in low yields (< 1 t.ha^{-1}); one reason could be the persistence of herbicides applied on previous wheat combined with severe heat during flowering and/or summer drought. As such, with irrigation, only 6 trials obtained yields (> 1.8 t.ha^{-1}) comparable to sunflower grown as main crop under rainfed management in the same regions.

However, under current climatic conditions, soybean and sunflower can only be grown in the South of Nouvelle-Aquitaine and Occitanie, where their requirements in growing degree days are fulfilled. In the North of Nouvelle-Aquitaine, physiological maturity was not achieved before autumn, which delayed too much harvest date, resulting in unsuitable conditions.

3.4 Irrigation costs are compensated by high selling prices

In 2019 and 2020, observed conventional prices of sunflower and soybean were relatively close, with a median of 345 €.t^{-1} for sunflower and 315 €.t^{-1} for soybean. In 2021 and 2022, the prices of both crops increased sharply up to 500–600 €.t^{-1} in 2021 and even 650–700 €.t^{-1} in 2022. However, due to poor yields, gross product was significantly lower for sunflower than for double crop soybean (P-value = 0.027; Fig. 9), with a median of 512 €.ha^{-1} compared to 805 €.ha^{-1}. It must however be specified that about one-third of the soybean trials were conducted on organic farms, where soybean grains were sold at 600–700 €.t^{-1} in 2019–2020, with no real differences with conventional prices in 2021–2022. Since these well-managed trials also obtained good yields (2–2.5 t.ha^{-1}), they resulted in higher gross products and semi-net margins than those of conventional farms.

The soybean and sunflower double cropping trials displayed very variable production costs, but this did not result in significantly higher costs for soybean (Fig. 10).

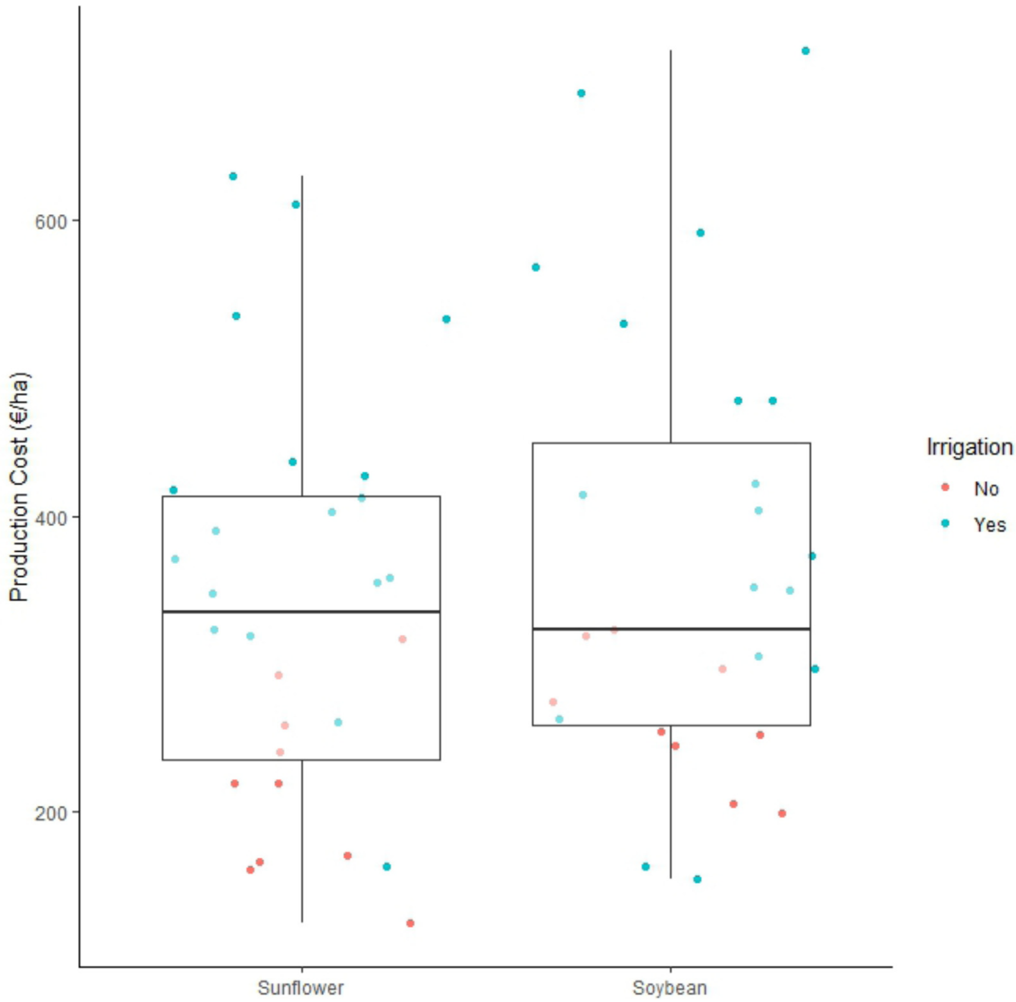

Fig. 10. Production costs (€.ha^{-1}) of sunflower and soybean grown as double crops within on-farm trials in 2019–2022 including non harvested situations (N = 55 fields: 28 sunflower, 27 soybean).

Consequently, semi-net margins were globally greater for soybean (P-value = 0.018), since both yields (1.9 t.ha^{-1} for soybean *vs.* 1.2 t.ha^{-1} for sunflower; P-value = 0.005), and gross products tended to be higher for this crop (Fig. 8). For both crops, the impact of irrigation on production costs was found significant (P-value = 4.2E-06) which led to an even lower semi-net margin for irrigated crops that have failed or obtained poor yield because of other limiting factors. But in spite of higher production costs, irrigated conditions resulted in higher gross products (P-value = 0.027) and SNM values (P-value = 0.010) for both crops.

In soybean, the costs of inputs ranged between 80 and 130 €.ha^{-1}, though one trial had higher costs (210 €.ha^{-1}) due to reinforced mechanical and chemical weed control (volunteers, complex weed flora). Farm seeds cost between 40 and 55 €.ha^{-1} and weed control between 10 and 45 €.ha^{-1}. Inoculation of soybean with symbiotic bacteria added 30 €.ha^{-1}. Adding to this irrigation (0.07 €.m^{-3}) and mechanical costs (soil tillage, weed control), very variable total production costs were estimated between trials: between 200 and 720 €.ha^{-1}, with a median at 350 €.ha^{-1}. The highest costs were observed in 2022 due to heavy irrigation with summer drought. However, increasing production costs was not detrimental to final income, because the trials with the highest production costs also belonged to organic farms with good yields and high commodity prices.

Double crop sunflower's production costs were similar to those of soybean (160–630 €.ha^{-1}, with a median at 360 €.ha^{-1}). Seeds were less expensive (in €.ha^{-1}) but certified seeds were systematically used as compared to soybean. Moreover, trials with direct seeding also required nitrogen fertilization. However, this was compensated by lower irrigation costs due to sunflower's relative tolerance to water stress when compared with soybean (Steduto *et al.*, 2012).

3.5 Balanced yields as a function of selling prices, production costs and harvest success

Based on the 2019–2021 and 2022 production costs (PC), we calculated for conventional sunflower and soybean crop management the "balanced yield" (for which SNM = GP-PC = 0) considering either a successful harvest every year (100%) or every two years (50%) (Figs. 11a and 11b). Each curve represents the minimum grain yield to achieve in order

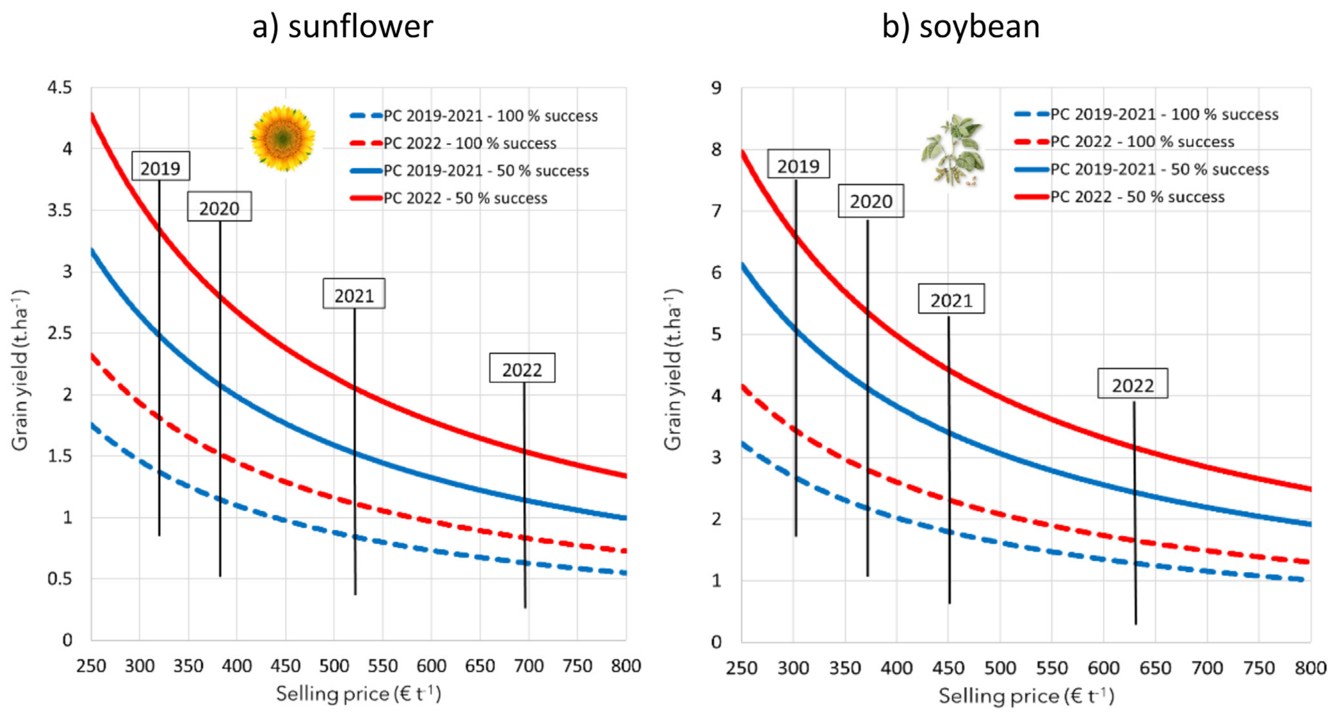

Fig. 11. Balanced grain yields (t.ha^{-1}) of sunflower and soybean grown as double crops as a function of selling prices (€.t^{-1}) for 4 scenarios of production costs (PC) and harvest success (every year – 100% or every two years – 50%).

to be profitable. The selling prices increasing from 2019 to 2022 were also displayed on the two figures. The crop practices applied to sunflower and soybean and the assumptions for production costs and selling prices are given in Table SI-2. We assumed an irrigation amount of 75 mm and 180 mm for sunflower and soybean respectively with higher costs than in the SYSTERRE® evaluation (0.20 and 0.30 €.m^{-3} in 2019–2021 and 2022 *vs.* 0.07 €.m^{-3}). Seed costs were also higher than in SYSTERRE® as we systematically opted for certified seeds in soybean (about 6 times more costly than farm seeds).

In sunflower (Fig. 11a), with a relatively low selling price in 2019, it was necessary to achieve at least a grain yield level of 1.4 t.ha^{-1} each year to be profitable. With increasing prices from 2020 to 2022, SMN could be positive for GY of 1.1, 0.8 and 0.6 t.ha^{-1} respectively. If crop harvest was successful only one year out of two, this will require a GY value of 2.5, 2, 1.5, and 1.1 t.ha^{-1} with increasing selling prices. In soybean (Fig. 11b), due to high irrigation and seed costs, the profitability of double cropping would require to reach each year 2–3 t.ha^{-1} which seems feasible with irrigation. The use of farm seeds could reduce the production costs. Growing soybean in southwestern part of Nouvelle-Aquitaine under rainy conditions could also increase the profitability of double cropping.

4 Conclusion and perspectives

The two SWOT charts (Tabs. 2 and 3) summarized the first conclusions in terms of feasibility, productivity and profitability of soybean and sunflower grown as double crops.

Those first results suggest that double cropping could be feasible in given agro-ecological conditions from southwestern France (adequate weather conditions and/or management systems, adapted machinery...). Soybean appears as the best candidate for double cropping in southern Nouvelle-Aquitaine and western Occitanie, with low economic risk. However, even though irrigation was not found to be a factor influencing semi-net margin (probably because of the high total production cost), double cropping soybean requires irrigation, except perhaps in the Béarn and Pays Basque (southwestern part of Nouvelle-Aquitaine) where rainfall is well distributed and sufficiently even in summer. Sunflower is another potential candidate, which was widely adopted in 2022, a very dry year but with previous crops early-harvested in June, although the economic risk seems higher, especially in rainfed conditions. Semi-net margins are less promising than for soybean, in large part due to low to medium yields. Sunflower as double crop should not be concentrated in the Occitanie region where the crop is still frequently grown as the main spring opportunity in order to prevent pathogen problems resulting from short rotations (*e.g.* mildew, phomopsis, phoma) (Mestries *et al.*, 2011). Furthermore, temperature requirements for these two crops are not fulfilled with a sufficient frequency in the North of Nouvelle-Aquitaine, in spite of very early maturing types; therefore, buckwheat remains the best potential candidate crop in this area (Ferrand, 2018).

As a research perspective, crop simulation could be attempted with longer climatic sequences (at least 20 years), in unexperimented soil-climate-management conditions, and on climate change scenarios to bring additional references on the feasibility and the productivity of this practice, especially by identifying the frequency of water shortage during plant

Table 2. SWOT (Strengths – Weaknesses – Opportunities – Threats) chart for soybean double-cropping in southwestern France.

Strengths	Weaknesses
High yields can be reached in favorable conditions (2.5–3 $t.ha^{-1}$), securing interesting semi-net margins Stable market outlets and interesting commodity prices (in particular for organic soybean) Harvest requires a leveled ground and/or adapted equipment (flexible cutter bar...)	High water needs, and potentially high irrigation costs Not suitable in the North of Nouvelle-Aquitaine because of the needs in growing degree days not fulfilled Post-harvest drying can be necessary
Opportunities	**Threats**
As a legume crop, residual soil nitrogen is expected Breeding programs in Europe for 0000 and 000 maturity groups	Increase sclerotinia risk at the crop rotation level Additional pressure on water resources in summer

Table 3. SWOT (Strengths – Weaknesses – Opportunities – Threats) chart for sunflower double-cropping in southwestern France.

Strengths	Weaknesses
Medium water requirements and moderate resistance to water stress Irrigation costs are lower than for soybean Seldom possible in the North of Nouvelle-Aquitaine due to GDD requirements Late physiological maturity can create lodging, grain loss, head fungal diseases	A small amount of irrigation is still required, especially for plant establishment Yields remain limited (max 1.8 $t.ha^{-1}$ in our trials) and observed commodity prices were variable Certified seeds are expensive Post-harvest drying can be necessary
Opportunities	**Threats**
Requires less water than double crop soybean Well-developed French sunflower sector Breeding programs in Europe for very early maturing cultivars groups	Increase sclerotinia (and other fungal diseases) risks at the crop rotation level

establishment and the risk of crop failure due to water stress and wet conditions at harvest (Schoving *et al.*, 2022). The STICS model (Brisson *et al.*, 2008; Brisson and Levrault, 2010) for instance could be used as well to calculate the irrigation requirements for different decision rules. This seems particularly useful to explore a wider range of climatic conditions before concluding on the feasibility and performances of double crops even if more than 100 on-farm situations over 4 growing seasons have been explored in the 3C2A project.

Furthermore, additional research is required to evaluate the benefits and drawbacks of double cropping when compared to cover crops which have shown promising agronomic and environmental impacts (Schipanski *et al.*, 2014). Double cash crops can create an additional income and transform regulatory constraints into opportunities in nitrate vulnerable zones (Callewaert, 2016). They could help develop some crop markets, for example in the grain legume sector. However, costs are higher than for cover crops, and the economic risk is also higher if the crop fails. Double cropping requires more working time and inputs than cover crops, including pesticides. Agronomic and environmental benefits are probably lower than those of cover crops, though double cropping allows soil coverage and reduces water and wind erosion risks. This could be evaluated using STICS model which successfully simulates the N and water dynamics in soils (Plaza-Bonilla *et al.*, 2015). However, the economic added value of double cropping is very hard to estimate in a context of strong climatic uncertainty and price volatility. A bioeconomic modelling approach would help comparing both fallow management practices.

Supplementary Material

Table SI-1: Monthly precipitation (mm) from June to September (2019–2022) for 9 weather stations located in the Nouvelle-Aquitaine and Occitanie regions (the numbers between brackets refer to the French department in which the weather station is located).
Table SI-2: Assumptions used for calculating the balanced yield ($t.ha^{-1}$) as a function of selling price (€.t^{-1}) for sunflower and soybean, grown as double crops with the most common crop practices according to two scenarios of production costs.

The Supplementary Material is available at http://www.ocl-journal.org/10.1051/ocl/2023016/olm.

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Authors contributions

All authors were partners of 3C2A CASDAR project. Nicolas Ferrand conducted the field data collection, Julie Pitchers, Manon Pull and Philippe Debaeke conducted the data analyses, Julie Pitchers and Philippe Debaeke led the writing of the manuscript. Sébastien Minette and Mathieu Abella contributed substantially to the manuscript through extensive revision.

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