High potential contribution of intercropping to soybean and maize self-sufficiency in Europe

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Abstract

The European Union is currently not self-sufficient in soybean and maize. Increasing domestic production of one of these species could reduce the production of the other. We examine the potential for maize-soybean intercropping to improve the European Union's soybean self-sufficiency while minimizing competition with maize and other crops. Assuming a one-in-four years frequency, 25%, 50%, and 75% self-sufficiency would be achieved with 6.3, 13.1, and 20.1 Mha of maize-soybean intercropping, resulting in total co-production of 37.9, 81.9, and 126.2 Mt of both crops, respectively. Meeting 100% of European soybean demand (i.e., 36.3 Mt) would require growing intercropping on more than 25% of European cropland (25 Mha) every year. To achieve comparable levels of co-production, separate cultivation of the two species would require an additional 36.5, 24.7, and 11.1 Mha of land, corresponding to an estimated land saving of 20–21% under intercropping. These estimates held provided that soybean production from 1 hectare of intercropping exceeded that from 0.5 ha of sole soybean. Ensuring the European Union's self-sufficiency in a sustainable way is a challenge requiring multiple levers. Our results underline that intercropping is an effective strategy to simultaneously improve European soybean production, satisfy maize needs, and save cultivated lands.

Keywords: Intercropping, soybean, maize, food security, self-sufficiency

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Introduction

With the onset of multiple geopolitical crises, as well as volatility in food supply and prices,[1] improving self-sufficiency has become a key priority of agricultural policies in the European Union (EU).[2,3] Every year, the EU uses large amounts of maize and soybean, especially for livestock feed.[4,5] Although maize self-sufficiency is relatively high (81%), soybean self-sufficiency did not exceed 16% in 2021-2022[6] (Supplementary Table 1). Moreover, EU's imports of soybean are mainly sourced from a small number of countries. In 2023-2024, 98% of soybean imports came from Brazil (45.4%), the United-States (40.7%), Ukraine (7.4%), and Canada (4.0%).[7] Increasing domestic soybean production is thus crucial to reduce EU's dependency on massive imports and their negative environmental impacts in both exporting and importing countries.[8,9]

Previous studies suggest that satisfying 50% of EU's consumption would require to grow 11.0-14.5 Mha of soybean,[10] representing a substantial increase compared to the 1 Mha currently grown on average over 2018-2022 in the EU.[11] Expanding croplands by converting natural ecosystems is unlikely, due to the scarcity of suitable land and the significant negative environmental impacts it would cause. Alternatively, soybean could substitute other crops, especially other spring crops with similar environmental niches such as maize.[10,12] However, substituting maize for soybean would lead to a reduction of the total maize production in the EU. It is thus crucial to identify sustainable strategies that foster EU's soybean self-sufficiency without compromising maize production.

So far, various scenarios of soybean area expansion in Europe have been explored in several studies, but they either overlooked the impact of soybean expansion on the production of other crops,[5,10,14,15] or neglected intercropping[12,16] – a practice still underdeveloped in Europe which consists in growing simultaneously multiple crops in the same field. Intercropping enhances land and nutrient use efficiency, making it a promising strategy for sustainable agricultural intensification.[17-19] In China, intercropping maize with soybean on 50% of the maize planting area could more than double the total soybean production in 2018 in this country.[20] An analysis of the potential of intercropping to sustainably boost the EU's soybean self-sufficiency is still lacking.

In numerous field studies, the efficiency of intercropping over sole cropping is examined using the land equivalent ratio (LER), which corresponds to the sum of the ratios of intercrop to sole crop yields over the different species of the crop mixture. The ratio obtained for a given species, called the partial LER (pLER), represents the sole crop area that would be needed to obtain the same production as the intercrop.[21] A global meta-analysis of 88 field studies estimated that 0.56 ha of soybean and 0.79 ha maize grown separately (i.e., a total of 1.35 ha) were required to produce as much as 1 ha of maize-soybean intercropping,[22] suggesting high potential of intercropping for land-saving compared to sole cropping. However, these field-scale estimates ignore the variability in maize[23] and soybean[10,12,14] yields across areas of contrasted productivity (e.g., due to climate conditions). Compared to intercropping, single cropping systems offer greater flexibility in terms of

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spatial distribution, as they allow production to be optimized by assigning each crop to its most productive area. If high-yielding areas in Europe are partly distinct for two crops, single cropping would allow farmers to allocate each crop to its highest-yielding region, while intercropping would involve growing at least one crop in low-yielding areas. It is therefore uncertain whether the large-scale adoption of intercropping would result in higher total production and land-use efficiency compared with sole cropping (see the detailed analysis of the productive performance of intercropping in case of spatial variability of yield in Supplementary Material 1).

In this study, we examine the potential of maize-soybean intercropping to improve soybean self-sufficiency in the EU while maintaining maize production. First, we estimate the area requirements under intercropping and sole cropping to meet 25%, 50% 75%, or 100% soybean self-sufficiency in the EU. Assuming that this level of soybean self-sufficiency is achieved, we then compare the efficiency of both strategies in maximizing both soybean and maize coproduction at the scale of the EU and quantify the land savings allowed by the most efficient strategy. The sensitivity of our results to variations in intercropping's productive performances, return frequency, and area of cultivation is also explored. Our findings suggest that maize-soybean intercropping could substantially contribute to EU's soybean self-sufficiency without decreasing maize production, while improving land use efficiency compared to sole cropping.

Results

Yield projections in the EU

Using historical (1981-2016) data of crop yield, water management, and climate in major producing areas of soybean and maize (Methods and Supplementary Figure 1), we train machine learning algorithms to predict rainfed yields of soybean and maize in the EU as a function of local climate conditions (2000-2023). The developed models show good predictive performances, as illustrated by their mean R^2 values of 0.93 for soybean and 0.91 for maize obtained from two cross-validation procedures assessing temporal and spatial extrapolation (Supplementary Figure 2) and by the symmetry of distribution of their residuals (Supplementary Figure 3). For both models, yield predictions are strongly impacted by total precipitation and water management, followed by temperatures (Supplementary Figure 4). Higher predicted yields are observed for higher precipitations and temperatures across the growing season, while lower yields are expected in dryer conditions (Supplementary Figures 5-9). These results are consistent with current knowledge on crop physiology of maize and soybean.[24,25]

The 25th, 50th (i.e., median), and 75th percentiles of averages soybean yield projections for 2000-2023 across the EU are 1.0, 2.1, and 2.6 t.ha^{-1}, respectively (Figure 1a, top panel). These levels of productivity are reached over 103, 82, and 36 Mha, respectively (Figure 1a, bottom panel), where

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wheat, maize, and barley are the major cultivated crops (Supplementary Table 2). The level of productivity of 1.0 $t.ha^{-1}$ also corresponds to the minimum yield observed in major soybean-producing regions with climatic conditions comparable to those of the EU of our train dataset (i.e., Italy and the US). Considering this threshold as a criterion for soybean suitability, our projections suggest that 103 Mha could be considered as suitable for soybean production in the EU, greatly exceeding the current European production area of 1 Mha (Supplementary Table 1). Compared to previous studies,[10,12,14] we obtain a larger share of soybean-suitable area in northeastern Europe, especially in Germany and Poland, but lower suitability in Spain. For maize under rainfed conditions, the corresponding 25th, 50th, and 75th percentiles of projected yields across the EU are 4.3, 6.2, and 6.9 $t.ha^{-1}$ (Figure 1b, top panel), attained over areas of 100, 62, and 27 Mha, respectively (Figure 1b, bottom panel). Our projections are consistent with historical maize yields in Europe,[26] excepted for Spain where our projections are slightly lower, maybe because of uncertainties about irrigation. High-yielding areas for both crops encompass a band in central EU stretching from southwestern France to the Balkan region, excluding the Alps (Figure 1c). On the contrary, areas with contrasting productivity between maize and soybean are found in Ireland, northern and southern EU.

How much land could be saved with intercropping?

Following the procedure displayed in Figure 2 and detailed in the Supplementary Material 2, we examine the potential of maize-soybean intercropping to improve soybean self-sufficiency in the EU while maintaining maize production.

First, we combine our yield projections with the productive performances of intercropping to estimate the potential quantity of soybean produced across the EU by a reference maize-soybean intercropping system. To represent the current average productive performance of maize-soybean intercropping systems, we assume as a baseline that 1 ha of intercropping produces as much as 0.56 ha of soybean and 0.79 ha of maize grown separately,[22] corresponding to pLER values of 0.56 and 0.79, respectively. We consider that intercropping is grown once every four years,[27,28] which means that the area cultivated under maize-soybean intercropping in a given site each year cannot exceed 25% of its cropland area.

We then estimate the area requirements under such a system to achieve 25%, 50%, 75%, and 100% soybean self-sufficiency in the EU (i.e., 9.1, 18.2, 27.2, and 36.3 Mt, respectively), assuming that intercropping would primarily be implemented in regions with the highest soybean productivity. We sequentially allocate intercropping to the most productive sites, ranked by soybean production (i.e. estimated by multiplying projected sole soybean yield by the cropland area in each site), until the whole intercropping area produces a quantity of soybean covering the

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considered level of self-sufficiency (i.e., 25%, 50%, 75%, or 100%) or exceeds 25 Mha, corresponding to a quarter of arable cropland areas in the EU.[29] We define this limit to avoid any extreme land use scenario leading to strong reductions of areas allocated to other crops (Supplementary Table 2), and because it is compatible with a soybean frequency of one-in-four year. Since intercropping involves that both soybean and maize are cultivated together in the same field and that maize's productivity remains above zero in the whole intercropping area (Figure 1), we also estimate the quantity of maize produced in this area.

Figure 3 presents the area requirements under maize-soybean intercropping to cover 50% soybean self-sufficiency in the EU (corresponding numbers provided in Supplementary Table 3). Producing enough soybean to reach this self-sufficiency level would require to preferably implement intercropping in southeastern part of France, North of Italy, Hungary, and Romania (first map in Figure 3a), where the production of soybean is the highest in the EU. The total area allocated to maize-soybean intercropping in this scenario covers 13.1 Mha (Figure 3b). This system would produce 18.2 Mt of soybean and 63.7 Mt of maize (Figure 3c), representing nearly a sevenfold increase in current EU soybean production while maintaining maize production at nearly the same level (Supplementary Table 1). In other words, 50% of the EU's soybean needs and nearly 75% of its maize demand could be met, thereby more than tripling the current self-sufficiency rate for soybean (16%), while slightly reducing the maize self-sufficiency rate from its current level (81%).

Then, we estimate the area requirements to reach the same soybean self-sufficiency levels but under a sole cropping system, following the same allocation procedure as intercropping assuming that sole soybean is sequentially allocated to the highest yielding sites. We find that 50% self-sufficiency could be reached by cultivating soybean on 7.1 Mha, as shown in Figure 3. The second map of Figure 3a shows the area required by sole soybean, while the third map represents the residual area of 6.0 Mha (i.e., 13.1-7.1 Mha) between intercropping and sole cropping. Based on our maize yield projections, growing sole maize on this remaining area would produce 39.0 Mt of maize, i.e., 39% less than the 63.7 Mt produced under intercropping for the same total area of 13.1 Mha (Figure 3c). To match the total co-production of 18.2 Mt of soybean and 63.7 Mt of maize achieved on 13.1 Mha of maize-soybean intercropping, an additional 3.4 Mha of sole maize would be required, mainly in Spain and in Easter EU, increasing the total land required by sole cropping to 16.5 Mha. These results indicate that intercropping can achieve similar co-production of both crops using 21% less land compared to sole cropping, while covering 50% EU soybean self-sufficiency. Similar results are observed for soybean self-sufficiency levels of 25% and 75%, for which intercropping allowed for 21% and 20% land saving compared to sole cropping, respectively (Supplementary Table 3).

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Land saving allowed by intercropping slightly decreases in simulations considering high N inputs and strong overlap between soybean and maize growing periods, two factors which were found to reduce maize-soybean intercropping efficiency.[22] Assuming N fertilization rates equivalent to those of maize in 2020 in the EU,[30] pLERs values varied from 0.45 and 0.59 for soybean and 0.77 and 0.79 for maize across the EU,[22] respectively (Supplementary Figure 10). In this case, intercropping uses 19% and 21% less land compared to sole cropping to achieve similar co-production of both crops considering the targets of 25% and 50% soybean self-sufficiency in the EU (Supplementary Table 4). Similarly, we obtain land savings of 16% and 18% when targeting 25% and 50% soybean self-sufficiency in a scenario where both species are sown and harvested at the same time (i.e., characterized by a temporal niche differentiation [TND] of 0), corresponding to pLERs values of 0.53 and 0.76 for soybean and maize,[22] respectively (Supplementary Table 5).

Potential contribution of a large-scale deployment of intercropping to EU's self-sufficiency

Our findings suggest that growing maize-soybean intercropping in soybean-suitable area every four years could substantially contribute to both soybean and maize self-sufficiency in the EU, while improving land use efficiency.

Considering that the total intercropping area could be as high as 25 Mha, corresponding to 25% of the 100 Mha total cropland in the EU in 2018,[29] our estimations indicate that maximum self-sufficiency levels of 91% for soybean and 145% for maize could be achieved with a conventionally managed intercropping system (i.e., one-in-four years cultivation, with a soybean pLER of 0.56 and a maize pLER of 0.79) (Figure 4). In these conditions, 33.1 Mt of soybean and 123.6 Mt of maize would be produced, representing a total coproduction of 156.7 Mt (Supplementary Table 3). Considering the same cropland area of 25 Mha, we estimate that allocating 14.8 Mha to pure soybean cultivation could achieve 100% soybean self-sufficiency in the EU. However, growing maize as sole crop on the remaining 10.2 Mha would result in 56% lower maize production compared to intercropping. Maize-soybean intercropping would thus benefit to EU's self-sufficiency not only in soybean, but also in maize.

The sensitivity of these results to variations in intercropping's productive performances, return frequency, and area of cultivation is also explored. Provided that 25 Mha is allocated to intercropping, we estimate that 29-100% soybean and 53-165% maize self-sufficiency are potentially achievable through intercropping, depending on return frequency and assumed pLER values (Figure 4). In particular, more than 53% and 84% self-sufficiency for each crop are achievable when pLER values remain equal to 0.56 for soybean and 0.79 for maize, respectively. Similar levels of self-sufficiency are achieved after incorporating the effects of N inputs and TND

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on the pLERs. In the analysis which incorporates the effect of N fertilization rates, the potential self-sufficiency rates range from 49 to 90% for soybean and 83 to 143% for maize, respectively, depending on the return frequency. Similarly, 49-90% and 80-138% self-sufficiency for soybean and maize, respectively, could be achieved in a scenario characterized by a TND of zero (i.e., corresponding pLERs values: 0.53 and 0.76), respectively (Supplementary Figure 11). More generally, when maintaining maize pLER at 0.79 while reducing soybean pLER to 0.5, 0.4, or 0.3, a minimum frequency of one year in six, five, or three is required to meet 50% soybean self-sufficiency, respectively (Figure 4a). With a one-in-four years frequency, 48-100% soybean self-sufficiency could be reached when soybean pLER varies from 0.3 to 0.7. It is worth noting that potential self-sufficiency rates achievable with intercropping always exceeds the current level in the EU for soybean, even in the least productive intercropping scenario (i.e., one-in-seven years frequency and 0.3 soybean pLER). To exceed the current maize self-sufficiency level in the EU, growing maize-soybean intercropping every six, five, and four years would be required with maize pLER values of 0.5, 0.6, and 0.7, respectively, assuming a 0.56 soybean pLER (Figure 4b).

Sensitivity analyses investigating the effect of variations in pLERs values for soybean (from 0.3 to 0.7, by 0.01-increment) and maize (from 0.5 to 0.9, by 0.01-increment) show a trade-off between the pLER values and the total allocated surface: as intercropping becomes more efficient for soybean production (i.e., as soybean pLER increases), less land is required to meet the soybean self-sufficiency target, thus reducing the production of companion maize (because the area allocated to intercropping decreases). To illustrate this, Supplementary Figure 12 shows the results of these sensitivity analyses when targeting 25% of soybean self-sufficiency (i.e., 9.1 Mt of soybean) in the EU. This level of soybean self-sufficiency is met as soon as soybean pLER is higher than 0.3 (panel a of Supplementary Figure 12). Consequently, maize production and intercropping area decrease as the value of soybean pLER increases, and this area reduction leads to a decrease of the total maize produced by the intercrops if the maize pLER remains unchanged. For example, when the soybean pLER increases from 0.3 to 0.56, the area required to produce 9.1 Mt of soybean decreases from 12.2 to 6.3 Mha, respectively (panel c of Supplementary Figure 12), reducing the companion maize production from 58.9 to 28.8 Mt when assuming a fixed value of maize pLER of 0.79. Increasing the maize pLER mitigates the decrease in the amount of maize produced by intercropping. When fixing the soybean pLER at 0.3, the minimum maize pLER values required to reach 50% and 75% of maize self-sufficiency levels are 0.58 and 0.86, respectively (panel d of Supplementary Figure 12).

Similarly, the level of 50% soybean self-sufficiency is reached as long as soybean pLER is higher than 0.31, assuming that 25 Mha is allocated to maize-soybean intercropping (panels a and c of Supplementary Figure 13). Interestingly, 50% soybean self-sufficiency and 100% maize self-sufficiency would be simultaneously achieved a maize pLER of 0.79 as soon as soybean pLER

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remains lower than 0.41. However, when soybean pLER exceeds this threshold, the area allocated to reach 50% soybean self-sufficiency decreases and maize self-sufficiency does not exceed 75% (panels b-c of Supplementary Figure 13). When targeting 75% or 100% soybean self-sufficiency using maize-soybean intercropping, one limiting factor was the maximum area allocated (Supplementary Figures 14-15). Within the constraint of 25 Mha (i.e., 25% of European cropland) of maize-soybean intercropping, a soybean pLER of 0.46 is required to meet three-quarters of the EU's demand in soybean, while achieving full soybean self-sufficiency would require a minimum pLER of 0.62.

Our main results are obtained assuming that soybean could be cultivated in all areas with a soybean yield higher than 1 $t.ha^{-1}$. If we restrict soybean cultivation to the 25% most productive sites only (i.e., sites with soybean yield ≥2.6 $t.ha^{-1}$), 11-98% soybean self-sufficiency could be achieved, depending on cropping frequency and soybean pLER (Supplementary Figures 16-17). On the opposite, extending soybean cultivation in several third countries and candidates for accession to the EU (Azerbaijan, Belarus, Norway, Switzerland, United-Kingdom, Albania, Bosnia and Herzegovina, Georgia, Moldova, Montenegro, North Macedonia, Serbia, Türkiye, Ukraine, and Kosovo) improves the potential soybean self-sufficiency levels attainable through intercropping (43-100%), especially in case of low return frequency (i.e., one-in-seven to one-in-four years cultivation) (Supplementary Figure 18). In this case, intercropping area shifts from northern and southern Europe to eastern Europe, especially in Ukraine, compared to the allocations performed for the EU only (Supplementary Figures 19).

Discussion

Extending the results from previous meta-analysis by taking into account spatial variability of intercropping in the EU, our study estimates the benefits of intercropping to improve EU's self-sufficiency in soybean, while maintaining high production of maize, and to quantify land saved by this strategy over sole cropping at a continental scale. Our results suggest that growing maize-soybean intercropping in areas most suited for soybean cultivation has the potential to enhance EU soybean and maize self-sufficiency, thus substantially reducing Europe's dependency to imported supplies. Based on geographical patterns of sole crops' yields, a one-in-four-year return frequency, and assuming that 1 ha of intercropping produces as much as 0.56 ha of soybean and 0.79 ha of maize in pure stands,[22] 13.1 Mha of intercropping could cover 50% and 75% of the EU's consumption in soybean and maize (i.e., 18.1 Mt of soybean and 63.7 Mt of maize), respectively. Intercropping outperformed sole cropping in maximizing maize-soybean co-production, allowing substantial land savings. For instance, to simultaneously produce 18.1 Mt of soybean and 63.7 Mt of maize, intercropping required 3.4 Mha (30%) less land than sole cropping, corresponding to an area slightly higher than the combined agricultural areas of Belgium and the Netherlands (1.4 and

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1.8 Mha, respectively).[29] Thus, maize-soybean intercropping emerges as a powerful strategy for improving food security and land use efficiency in the EU.

Previous research has shown that the productive performances of intercropping are highly variable, with LER values ranging from less than 0.5 to more than 2.0 for maize-soybean intercropping on the global scale.[22] While intercropping scenarios characterized by pLERs values >0.5 for soybean and > 0.7 for maize lead to higher improvements in self-sufficiency and land savings, our results suggest that intercropping maize and soybean in the EU remains an interesting option to improve self-sufficiency compared to sole crops even with lower pLERs. In this study, intercropping's contribution to maize and soybean self-sufficiency slightly decreased with higher N inputs or when maize and soybean were grown during the same period, but still strongly improved self-sufficiency compared to the current EU level. These results highlight the importance of identifying combinations of environmental conditions and management practices that maximize the benefits of this strategy.

Many factors affecting the performances of intercropping have been identified in previous research. For example, results from a meta-analysis of field trials conducted in China[32] suggest that increased sunshine hours and temperatures would reduce the performance of maize-soybean intercropping compared to sole crops. It has been shown that due to interspecific competition, soybean often underperforms relative to maize in intercropping,[33] particularly under increased nitrogen fertilization[22] and nutrients availability.[32] However, wider strip distance,[34] moderate maize planting density, or shorter growth periods' overlap[32] could contribute in reducing the competition between species in intercrops. In Europe, the performance of cereals-legumes mixtures is also affected by climate conditions, especially rainfall, and farming practices such as tillage, and nature and quantity of applied fertilizers.[35] Given the limited information on the interaction between soybean productivity in intercropping and other farming practices in Europe, additional trials are required to refine local estimations of maize-soybean intercropping performances and to help identifying the best combinations of field configuration, fertilization, and water management which maximizes the productivity of intercropping at the farm level.

Although several studies suggest that deploying intercropping in Europe could provide agroecological benefits while maintaining crop productivity,[36] its development is hampered by numerous barriers[37,38] throughout the food value chain, but predominantly faced by farmers.[39] Tackling the farmer-specific barriers is necessary but insufficient to promote widespread adoption across the EU.[37,39] For instance, intercropping requires specific machinery for sowing, harvesting, and sorting of grains of the different crops to comply with collectors and processors purity standards. In addition, adapted irrigation systems and crop protection practices still need to be identified, also according to intercropping design. Large-scale introduction of intercropping could create a significant market, driving the development of affordable, specialized machinery. However,

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such equipment will not be sufficient to make intercropping a viable system if purity standards are not adapted to intercropping products. Given the systemic nature of these barriers, involving all stakeholders across the value chain is essential for designing effective policies to unlock the full potential of legume-cereal intercropping in Europe. On the positive side, since genetically modified crops are only marginally grown in the EU, the soybean produced in EU will be non-genetically modified, and will therefore address a specific market, different from that for genetically modified soybean from North and South America. Additionally, adopting maize–soybean intercropping would alter crop sequences, likely reducing the temporal frequency of some crops (e.g. maize) while increasing that of others (e.g. soybean). Such increases in temporal crop diversity within rotations offer multiple agronomic benefits, including improved control of pests, diseases, and weeds, as well as enhanced nitrogen management (particularly when including legume crops) with positive effects on crop yields.[40,41] However, quantitative evidence on the effects of crop sequences that include maize–soybean intercropping remains limited. Although a few studies exist,[42] the available data are currently insufficient to support robust assessments.

One strength of this study is the use of a machine learning model to model soybean and maize productivity trained on a global historical yield dataset.[43] Thanks to their greater flexibility, machine learning algorithms often outperform traditional methods (e.g., linear regression or process-based models) to forecast yields of crops from climate predictors, especially soybean[44,45] and maize.[46] For soybean, a limitation of the model is the low number of observations collected in Europe as few data points were available in Europe to train the model for soybean, which may affect prediction accuracy. Our results highlight that maize-soybean intercropping performs well under current climate, but the suitability of this cropping strategy in future climate conditions has not been examined in our analysis. Previous studies[10,14] suggest that by 2050, climate change may shift soybean-suitable area in Europe, with northern regions becoming more favorable and lower latitudes increasingly less suitable.[47,48] Overall, it has been shown soybean production in Europe is likely to increase under various climate change scenarios compared to historical conditions.[10,48] On the contrary, maize yields are expected to decline, with an estimated 10% loss per degree Celsius increase if no adaptation strategies are implemented.[46] However, maize was found to be highly responsive to adaption strategies, such as irrigation and cultivar adaptation, which could mitigate future yield losses, especially in higher latitudes like Europe.[46,49] More research is needed to assess the robustness of our findings in light of these potential changes in the spatial yield patterns of soybean and maize. With the possible reduction of the lengths of growing periods in the context of climate warming, the cultivation of several crops during one single growing season (i.e., relay or double cropping) might become more plausible in some regions.[50,51] However, a

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comprehensive analysis of the relative interest of these practices compared to intercropping is lacking.

Our findings suggest that to achieve 91% soybean self-sufficiency, more than 25 Mha of maize-soybean intercropping would be required, corresponding to an increase of 15 Mha compared to the current harvested areas of maize and soybean in the EU.[11] Although maize-soybean intercropping offers advantages in terms of productivity,[52] a large-scale deployment of this type of intercrop would compete with other crops that play an important role in feed and food production, such as barley and sunflower. To limit this problem, it would be advisable to diversify the types of intercropping and consider the use of double cropping systems, i.e. systems with two crop harvests per year, in regions where this system could be implemented.[10,45,53] Potential production from other intercropping systems and double cropping systems deserves further research.

An alternative strategy to reduce EU dependency on soybean imports is to decrease the soybean demand. This could be achieved by growing other legume crop species (e.g., broad bean, pea, and lupin) as feeds[16] or by switching to a less meat-based diet with lower meat consumption by humans.[5] The latter was found to reduce the demand for soybean-based protein in the EU through lower meat consumption, and free up land to produce more legume crops for human consumption rather than livestock feed. In the future, an integrated strategy combining both an increase in supply through intercropping and a reduction in demand through a partial change in diet would enable Europe to reduce its dependence on imports of agricultural commodities without too much impact on its cultivated areas.

Methods

Yield projections in the EU

We developed models to forecast soybean and maize yields in the EU – referring as the EU from February 1^{srt} 2020, when the United Kingdom withdrew – as a function of climate conditions and water management. For both crops, we built training a dataset including gridded data on historical worldwide yields collected in major producing areas,[43] irrigated fraction from the SPAM2010 database,[54] daily minimum and maximum temperature (°C), total precipitations (mm), solar radiations (MJ.m^{-2}), evapotranspiration (mm.day^{-1}), and vapor pressure deficit (kPa) from the ERA5-Land database.[55] For each site, we expressed annual yield data relatively to the expected value at the most recent year of available (i.e., 2016). This detrending procedure allowed to remove the systematic temporal component of yield that is attributed to technological progress (e.g., genetic improvement, management, inputs) and to focus on the interannual variability around that trend, which is typically interpreted as being driven by climate, weather, soil, or other non-progress-related factors. Further details on data pre-processing steps are provided in

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Supplementary Material 3. The total number of sites (resp. number of sites-year) included in the soybean and maize datasets reached 3,286 (116,516) and 2,064 (72,964), respectively. In production sites, detrended yields ranged from 0.1 to 6.7 $t.ha^{-1}$ for soybean and from 0.5 to 20.0 $t.ha^{-1}$ for maize (Supplementary Figure 20). The minimum yields observed in the train dataset for major regions producing soybean with climatic conditions comparable to those of the EU (i.e., Italy and the US) and major maize-producing regions in the EU were 1.0 and 1.3 $t.ha^{-1}$, respectively. Mean (standard deviation) yield, representing the average (standard deviation) of values rescaled to the technological baseline of 2016 and independent of the original calendar years of observation, was 2.6 $t.ha^{-1}$ (1.1 $t.ha^{-1}$) for soybean and 9.5 $t.ha^{-1}$ (3.8 $t.ha^{-1}$) for maize. Exclusively rainfed soybean or maize were grown in 45% and 24% of sites, respectively. Within sites with fractional area of irrigated soybean or maize exceeding 0%, irrigated soybean and maize represented 1-22% and 1-30% of cultivated area of each crop, respectively.

We tested different approaches to predict soybean and maize yields (Supplementary Material 4). The choice of the models was guided by previous works comparing various techniques to aggregate climate predictors and various algorithms to predict soybean yield.[10,44] These studies showed that the first two principal components (PCs) were able to capture large variations in monthly climate averages and using these PCs in a random forest algorithm provided highly accurate predictions of soybean yields in rainfed conditions. Following this methodology, we built distinct predictive models for both crops, as well as variants based on different climate data aggregation methods (i.e., monthly average, seasonal average, or a higher number of PCs) for comparison. For each crop, the model based on the first two PCs showed the best transferability in time and space according to two cross-validation procedures (Supplementary Material 4). Based on this approach, we projected the annual yields of rainfed soybean and maize in pure stands in 2699 sites EU over 2000-2023 (i.e., 64776 site-year) using climate and irrigation data from the ERA5-Land database[55] and water management from the SPAM2010 database[54] as predictors. Except for soybean yields ≥3.0 $t.ha^{-1}$ and maize yields ≥7.0 $t.ha^{-1}$, projections were not sensitive to the models selected (Supplementary Figure 21).

Performance of intercropping to maximize soybean and maize co-production in the EU

We estimated the yield of both crops when cultivated in intercropping by multiplying the projections of yields in pure stands and rainfed conditions by their respective value of pLER (i.e., 0.56 and 0.79, respectively) obtained from a meta-analysis of soybean-maize intercropping trials.[22] Results of this meta-analysis were estimated using 654 field observations collected in 108 sites worldwide, with environmental conditions partially representative to those in the EU (Supplementary Figures 22-23). Although this meta-analysis also provides an estimation based on data collected in Europe specifically, we choose to use the global estimate, which is slightly

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less optimistic (i.e., lower pLER), preventing us to overestimate the productivity of intercropping. We then estimate the production of soybean and maize as the product of predicted intercropping yields, site-specific cropland area from the SASAM dataset,[56] and a coefficient representing the return frequency of intercropping in crop sequences. We set this coefficient at 1/4, corresponding to a one-in-four years return frequency to limit the risk of pests and diseases[27,28] and which is equivalent to allocating each year 25% of the cropland area *in each site*.

Based on these estimates, we examined the potential of intercropping to improve EU's soybean self-sufficiency while limiting competition with other crops by performing allocation scenarios of maize-soybean intercropping across the EU. Our allocation process was guided by three assumptions: (1) maize-soybean intercropping would be preferentially implemented in areas with the highest projected soybean yields but (2) excluding sites with unsuitable conditions for soybean production (i.e., projected yields below 1 $t.ha^{-1}$, corresponding to the minimum observed in the training dataset from the US and Italy; Supplementary Figure 20); and (3) to limit cropland expansion and competition with other crops, total area allocated to intercropping *at the scale of the EU* should not exceed 25 Mha, equivalent to 25% of EU cropland in 2018[29] or to the area devoted to wheat, the most widely cultivated crop in the EU over 2018–2022.[57] In the area allocated to maize-soybean intercropping, the minimum maize yields projections (ranging from 3.7 to 4.0 $t.ha^{-1}$ depending on the considered scenario) were three-to-four times higher than the minimum yield of 1.3 $t.ha^{-1}$ observed in our train dataset of maize-producing regions in the EU (Supplementary Figure 20). Considering this, no additional criterion was considered for maize suitability in the allocation procedure.

For each allocation scenario, maize-soybean intercropping was sequentially allocated to highest yielding sites, ranked by soybean productivity (i.e., projected soybean yields), until P_S^* was reached or until the total area allocated to intercropping reached 25 Mha. This allocation yielded to simultaneously produce P_S^* Mt of soybean and P_M^i Mt of maize, co-produced through intercropping. The total co-production (i.e, $P_S^* + P_M^i$) was calculated and compared to the one obtained with a sole cropping strategy applied over the same total cropping area (i.e., the area required to reach P_S^* with intercropping). For the sole cropping strategy, we first allocated sole soybean to the highest yielding sites until reaching P_S^* or 25 Mha. Second, we allocated sole maize to the remaining sites and computed the resulting maize production in maize monocrop P_M^m. Note that, in this approach, the sum of the sole soybean area and the sole maize area is equal to the intercropping area obtained with the intercropping allocation strategy previously described.

Since both allocation procedures were designed to produce P_S^* Mt soybean, the most efficient strategy among intercropping (i.e., simultaneous cultivation of maize and soybean in the same area) or sole cropping (i.e., separate cultivation in different areas) was the one leading to the

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largest production of maize in the region of interest. We performed four distinct allocation scenarios considering values of P_S^* of 9.1, 18.2, 27.2, and 36.3 Mt, equivalent to soybean self-sufficiency levels of 25%, 50%, 75%, or 100% in the EU, respectively, based on the average EU soybean consumption of 36.3 Mt over the 2018–2022 period.[11] For each scenario, we estimated the areas required by intercropping and sole cropping. Based on these estimates, land saving allowed by the most efficient strategy over the least efficient one was estimated as the difference between the area required by the least efficient strategy to reach the same level of co-production than the most efficient strategy, divided by the area required by the most efficient strategy. Further details regarding procedure to allocate and compare sole and intercropping strategies are provided in Supplementary Material 2.

Sensitivity analyses

To assess the sensitivity of our results to cropping frequency, the main analysis (i.e., pLER values of 0.56 for soybean and 0.79 for maize, respectively) was repeated in scenarios specified by combining different values of crop frequencies (one-in-seven to one-in-two years, by yearly increment), soybean pLER (0.3 to 0.7, by 0.1-increment) and maize pLER (0.5 to 0.9, by 0.1-increment). These values of pLERs corresponded to LER ranging from 0.8 to 1.6, in the range of the possible values of maize-soybean LER estimated by Xu et al.[22]

The results of Xu et al.[22] show that soybean pLER vary according to fertilization practices, especially N inputs but also depending on the overlap between growing periods of maize and soybean, characterized by the TND. High TND values (i.e., close to 1) correspond to small overlap, where the second species is sown just before the harvest of the first crop (e.g., relay intercropping), whereas a TND of zero represents systems in which both species are sown and harvested simultaneously. To evaluate the effects of high N inputs and TND on values of partial land equivalent ratios (pLERs) of soybean and maize, we used the regression models published by Xu et al.[22] to compute less optimistic pLER values (i.e. lower) assuming high N fertilizer doses and low TND and assessed the robustness of our conclusions considering these lower pLER values. First, to take into account the spatial variability in N management in the EU, we computed site-specific soybean and maize pLERs according to local N fertilizer application rates of 2020 provided by the NPKGRIDS gridded dataset[30] using published regression model.[22] To compute less optimistic pLER values (i.e. lower) assuming high N fertilizer doses, we considered that the applied N fertilizer rates were those of maize, which receive higher amounts of N. Supplementary Figure 10 shows the applied rates, as well as derived pLER values. Second, we assumed that both species had

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identical growing periods (i.e., TND=0), which led to pLER values of 0.53 and 0.76, respectively. Further details these sensitivity analyses are provided in Supplementary Material 5.

Additionally, for the different soybean self-sufficiency levels considered in this study (i.e., 25%, 50%, 75%, and 100%), we considered scenarios with pLER varying values of soybean (0.3 to 0.7, by 0.01-increment) and maize (0.5 to 0.9, by 0.01-increment) to increase the range of possible performances of intercropping over sole cropping. We estimated the minimum pLERs conditions simultaneously satisfying each soybean self-sufficiency levels, as well as 25%, 50%, 75%, and 100% maize self-sufficiency, given a one-in-four-year return frequency and limiting the surface allocated to 25% of the cropland area in the EU.

To explore the impact of concentrating intercropping in the high-yield sites, allocation procedures were repeated for sites where the average soybean yield exceeded 2.6 $t.ha^{-1}$ (instead of 1 $t.ha^{-1}$) representing the 75th percentile of projected soybean yields. The impact of expanding soybean cultivation in several third countries and candidates for accession to the EU was explored as well.

All data analyzed in this paper are publicly available in associated publications, including maize and soybean historical yields,[43] water management,[54] and climate conditions.[55] All relevant R (version 4.3.1 http://www.r-project.org) scripts, python script used to run and set parameters of the Copernicus Climate Data Store API, and documentation are available via the project repository on Github at https://github.com/MathildeChen/Maize_Soybean_Intercropping_Europe.

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Figures

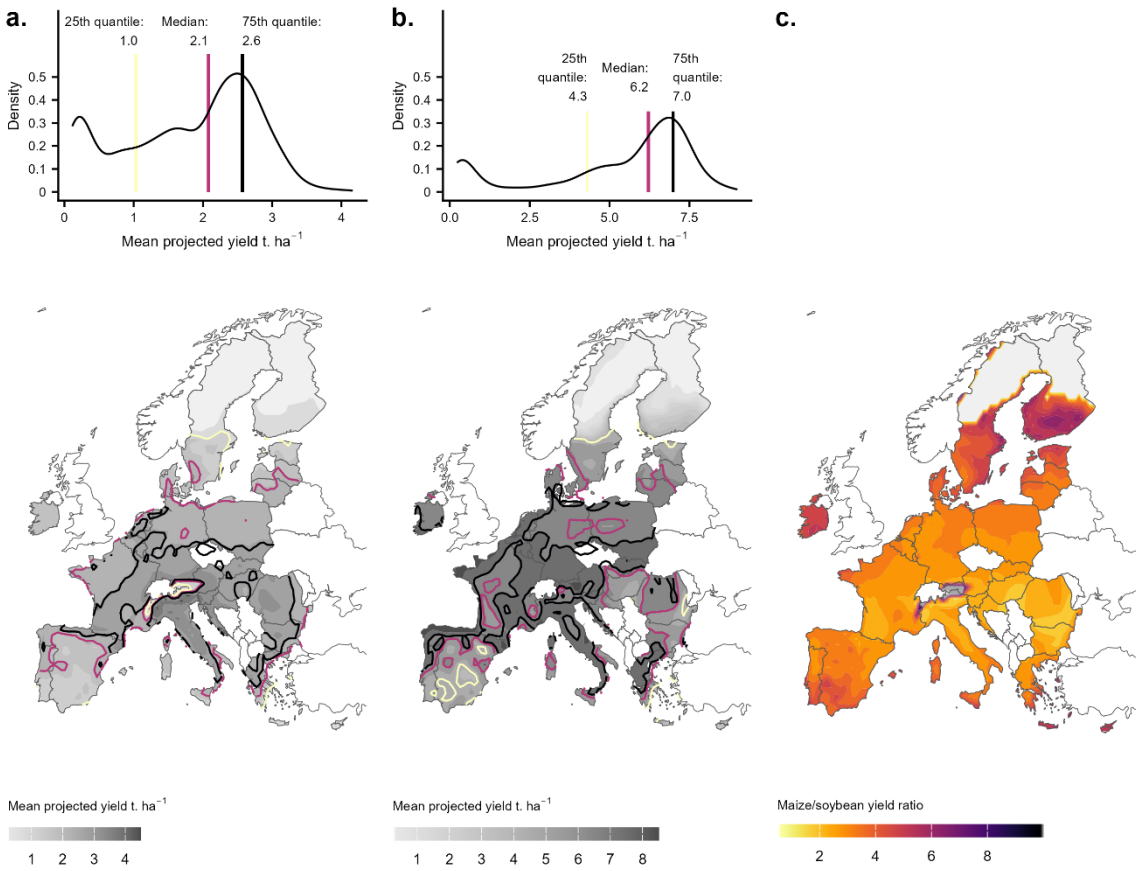


Figure 1. Soybean (a) and maize (b) rainfed yield projections (2000-2023 averages), and maize/soybean ratio (c) in the European Union. Projections were obtained from random forest models based on climate inputs (derived from the ERA5-land dataset) covering the crop growing seasons (April-November for soybean and April-December for maize) and irrigated fraction (estimated by SPAM2010, and set to zero for the yield projections). Climate inputs included monthly averages of minimum and maximum temperatures, total precipitation, solar radiation, reference evapotranspiration, and vapor pressure deficit. For each climate variable, the first two scores derived from a principal component analysis were used as climate predictors in the model. For panels (a) and (b), density graphics on the top show the variability in average projected yields, with 25th, 50th (median), and 75th quantiles indicated as vertical yellow, red, and black lines, respectively. Below, the maps represent the spatial distribution of projected average yields, with darker shades indicating regions with higher mean yields, whereas lighter shades representing lower yields (e.g., areas with average crop yield ~ 0 t.ha^{-1} are displayed in light grey). Regions corresponding to the 25th, 50th (median), and 75th yield quantiles are further delineated by yellow, red, and black contours, respectively. For panel (c), darker shades indicate high ratio between maize and soybean average projected yields, for example in the areas close to the Alps characterized by low soybean yields (i.e., <1 t.ha^{-1}) but moderate-to-high maize yields (i.e., >6 t.ha^{-1}).

Question:
How much land could be saved with intercropping to produce a given quantity of soybean (P_S^*) in the European Union (EU)?

1. **Allocation procedure of maize-soybean intercropping (Int.) and maize and soybean grown separately (SC) based on soybean productivity:**
   - ➔ sequentially, in areas ranked soybean productivity
   - ➔ if conditions are suitable for the production (projected yield of soybean ≥1 t.ha^{-1})
   - ➔ stop → if P_S^* is reached or if total area allocated ≥ 25 Mha**

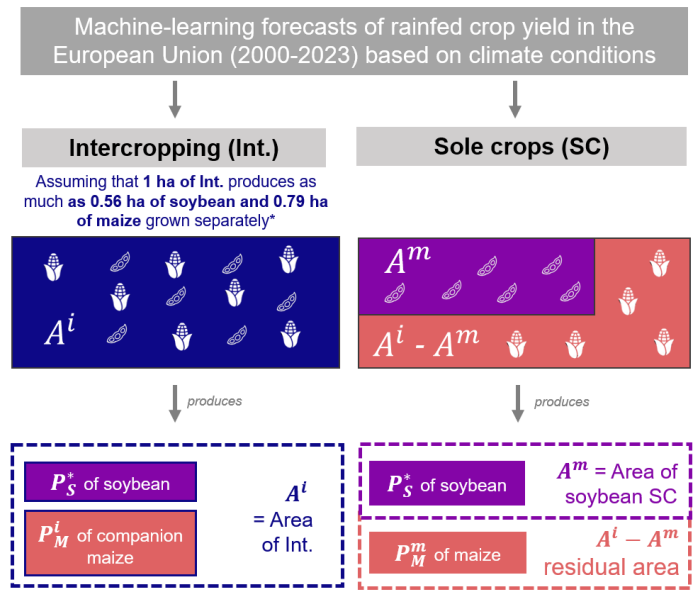
2. **Compare the total crop production for the same area**
   - ➔ Int. = P_S^* of soybean + P_M^i of companion maize are both produced on A^i (= total area allocated to Int.)
   - ➔ SC = P_S^* of sole soybean on A^m (area allocated to soybean) + P_M^m of sole maize on the residual area $A^i - A^m$

3. **Estimate land savings**

   Across the EU, how much **additional land** is required so that:

   P_S^* of soybean + P_M^i of maize
   =
   P_S^* of sole soybean + P_M^m of sole maize

*corresponding to partial land equivalent ratios of 0.56 and 0.79, respectively.
Values extracted from Xu, *et al.* (2020). Intercropping maize and soybean increases efficiency of land and fertilizer nitrogen use; A meta-analysis. *Field Crops Research* 246:107661.
** representing 25% of the European cropland, in order to avoid competition with other crops



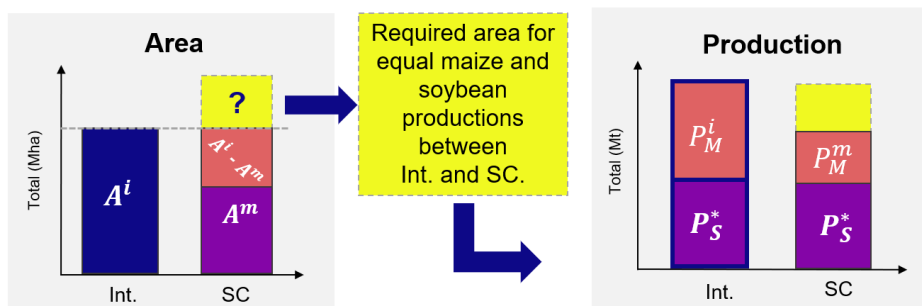


Figure 2. Procedure applied to estimate the area requirements under intercropping (Int) and sole cropping (SC) to meet a target soybean production (P_S^*) in the European Union (EU), to compare the efficiency of both strategies in maximizing both soybean and maize coproduction, and to quantify the land saving allowed by the most efficient strategy at the scale of the EU.

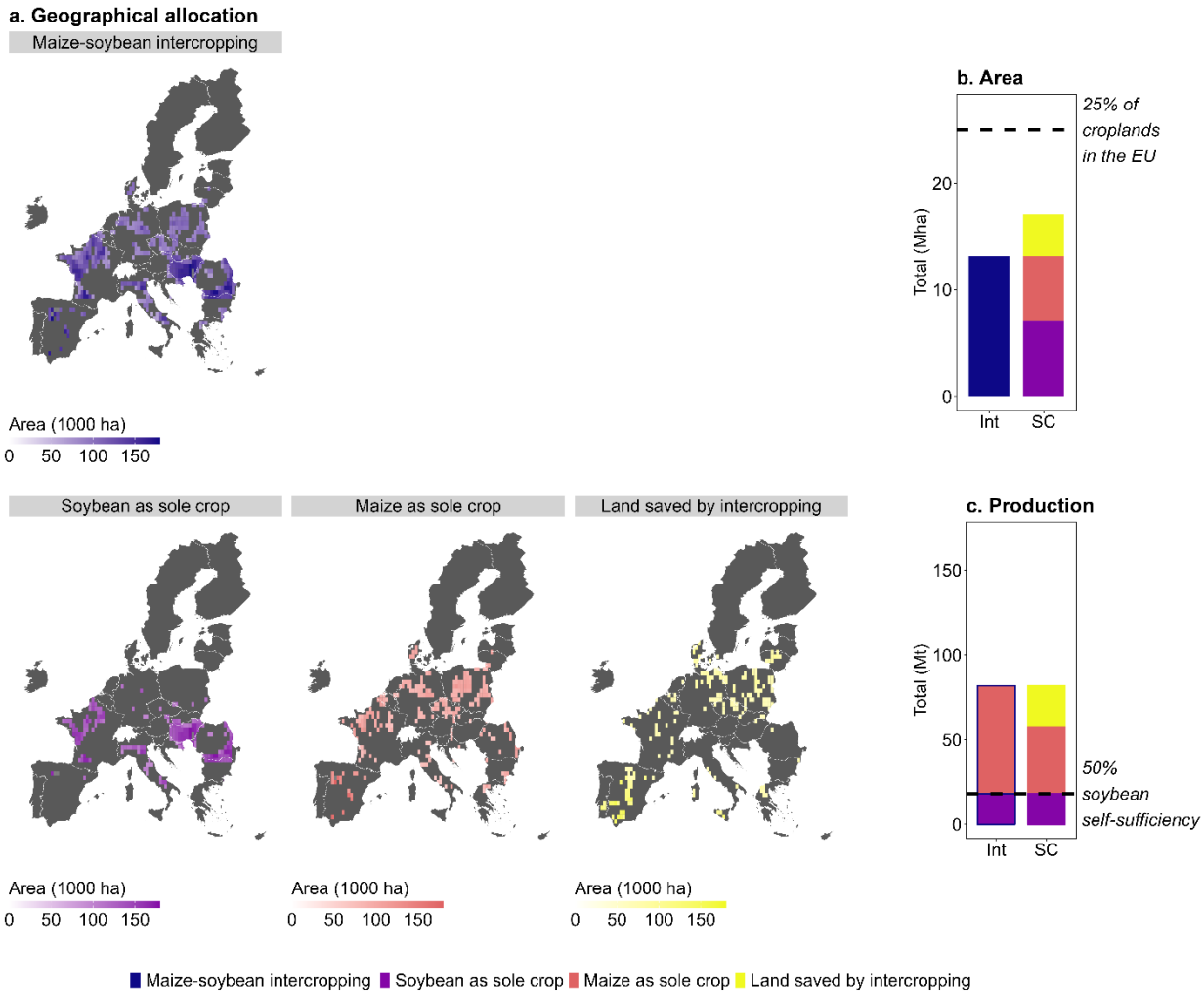


Figure 3. Comparison of maize-soybean intercropping (Int) and sole cropping (SC) for 50% soybean self-sufficiency in the European Union (EU). Maize-soybean intercropping was sequentially allocated in highest yielding sites, ranked by soybean productivity based on mean average production over 2000-2023 period in rainfed conditions, until 50% soybean self-sufficiency (i.e., 18.2 Mt) is reached. Sole soybean was sequentially allocated in the highest yielding sites until reaching 50% soybean self-sufficiency, then sole maize was allocated to the remaining sites so that the total covered area is equal in both strategies. Panel (a) displays the geographical allocation of crops with the Int. (top map) and with the SC (bottom maps) strategies. In the SC strategy, the two first maps represent the allocation of sole soybean and sole maize, respectively, while the third map shows the additional area required to produce the same coproduction than in Int. Panels (b) and (c) show the corresponding area requirements and maize-soybean co-production, respectively. All simulations are based on (i) yield projections from a random-forest model based on the two first principal components of climate variables and irrigation fraction (set to zero here), (ii) crop return frequency of one year in four, and (iii) partial land equivalent ratios equal to 0.56 and 0.79 for soybean and maize, respectively.[22] The maximum total allocated area was set at 25% of croplands in EU, indicated as dotted line in the panel (b). Self-sufficiency levels of 50% corresponds to soybean, indicated as horizontal dotted line in the panel (c).

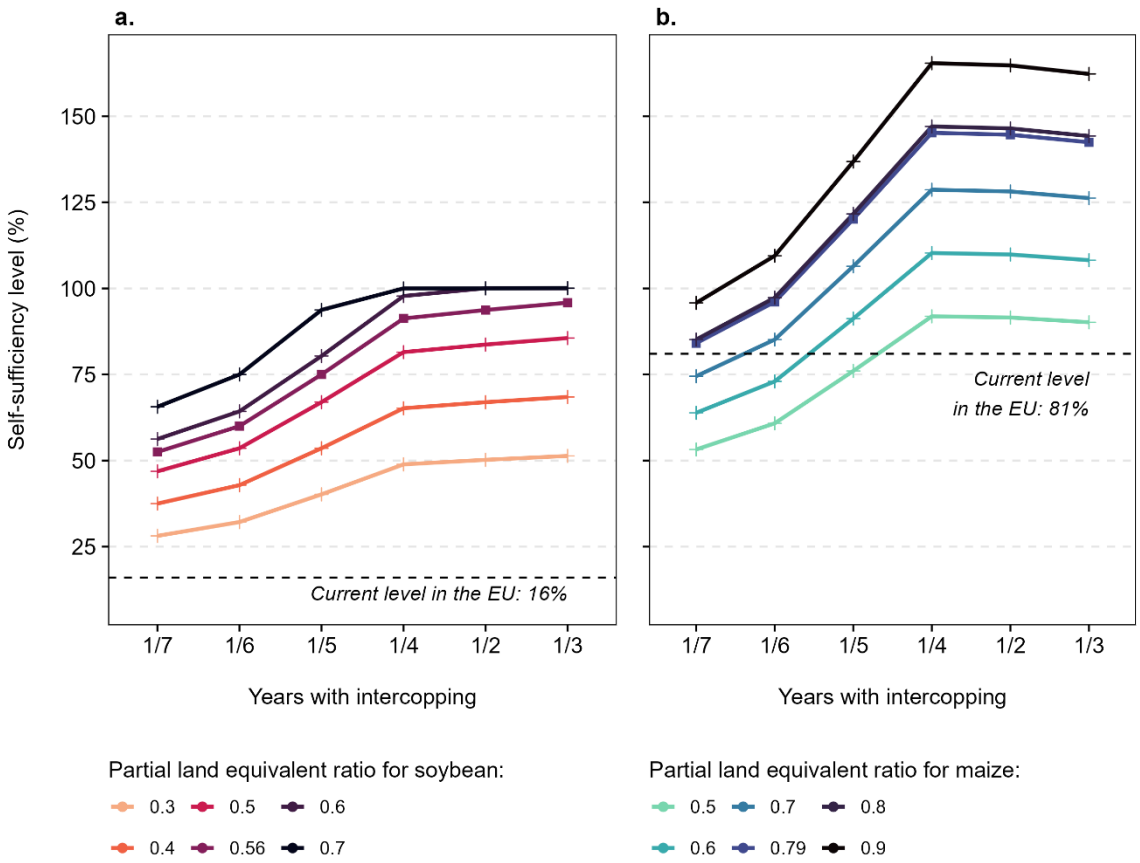


Figure 4. Levels of soybean (a) and maize (b) self-sufficiency in the European Union (EU) achieved from intercropping for different assumptions of partial land equivalent ratio (pLER) and crop return frequency.

Crop frequencies of one year in seven, six, five, four, three, or two correspond to allocating maize-soybean intercropping on 14%, 16%, 20%, 25%, 33%, or 50% of cropland area in each grid-cell. Intercropping was first allocated to soybean highest-yielding grid-cells, and in all cases total intercropping area was constrained to not exceed 25% of croplands in the EU (i.e., 25 Mha). Squares represent the results obtained with average productive performances of maize-soybean intercropping systems (i.e., pLER of 0.56 for soybean and 0.79 for maize) estimated in a previous meta-analysis.[22]

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