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. We examine the potential for maize-soybean intercropping to improve the European Union's self-sufficiency in both crops without cropland expansion and by minimizing crop substitution. Maize–soybean intercropping, even limited to 25% of croplands in the European Union, could meet 25%, 50%, and 75% of soybean demand with 6.3, 13.1, and 20.1 Mha, respectively. Full self-sufficiency would require exceeding this threshold. When comparing the areas of cultivated land obtained by growing both species separately or together, intercropping could save 27-30% of land as soon as more soybean is produced in 1 ha of intercropping than in 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 became 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] 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. Additionally, this strategy is expected to increase water deficit and irrigation needs because soybean has a relatively shallow rooting system compared to maize.[13] 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-

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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 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 quantified 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 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

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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]

Soybean yield projections for 2000-2023 reveal large areas with good suitability for rainfed soybean in the EU (Figure 1a). Considering a threshold of 1.0 $t.ha^{-1}$ (i.e., minimum observed yield in major soybean-producing regions of our training dataset with climate conditions similar to those in the EU and to the 25th percentile of our projections under rainfed conditions), our projections suggest that 103 Mha could be considered as suitable for soybean production in the EU. The median projected soybean yield of 2.1 $t.ha^{-1}$ (75th percentile: 2.6 $t.ha^{-1}$) is attained across 82 Mha (resp. 36 Mha), largely 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, projected rainfed yields are equal to or higher than the median historical yield of 6.2 $t.ha^{-1}$ (75th percentile: 6.9 $t.ha^{-1}$) on 62 Mha (resp. 27 Mha) (Figure 1b). 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 combine the yield projections with the productive performances of intercropping estimated from a global meta-analysis[22] to examine the potential of maize-soybean intercropping to improve soybean self-sufficiency in the EU while maintaining maize production. Then, we quantify the land savings allowed by intercropping at the scale of the EU.

First, we estimate the area requirements under maize-soybean intercropping to meet 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 and excluded from those with lowest suitability (i.e., soybean yield below 1 $t.ha^{-1}$). To represent the current average productive performance of maize-soybean intercropping systems, we assume 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 is equivalent to yearly allocating 25% of the cropland area in each site to intercropping. To limit competition with other crops, we consider that intercropping could not be implemented on more

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than 25 Mha, corresponding to a quarter of cropland areas in the EU.[29] Additionally, since both soybean and maize are simultaneously cultivated in such system 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. For example, producing enough soybean to reach 50% self-sufficiency would require to preferably implement intercropping in southeastern part of France, North of Italy, Hungary, and Romania (first map in Figure 3a), covering an area of 13.1 Mha (Figure 3b). This system would simultaneously 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. 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, 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 30% less land compared to sole cropping, while covering 50% EU soybean self-sufficiency. Similar results are observed when considering the soybean self-sufficiency levels of 25% and 75%, for which intercropping allowed for 27% and 29% land saving compared to sole cropping, respectively (Supplementary Table 2).

Land saving allowed by intercropping slightly decreased in simulations considering high N inputs and stronger competition between intercropped species, two factors which were found to impact maize-soybean intercropping efficiency.[22] Assuming a N fertilization rate of 148 $kg.ha^{-1}$ (i.e., 75th of N rate applied on maize in the EU in 2017-2018)[30] and corresponding to pLERs values of 0.51 and 0.78 for soybean and maize,[22] respectively, intercropping uses 24% and 22% less land compared to sole cropping to achieve similar co-production of both crops using targeting 25% and 50% soybean self-sufficiency in the EU (Supplementary Table 3). Similarly, 20% and 23% self-sufficiency for soybean and maize, respectively, could be achieved in a scenario characterized by a TND of zero (i.e., both species are sown and harvested at the same time) and corresponding pLERs values of 0.53 and 0.76,[22] respectively (Supplementary Table 4).

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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 conventional intercropping system (i.e., one-in-four years cultivation, with a soybean pLER of 0.56 and a maize pLER of 0.79) (Supplementary Table 2). 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. 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 pLER values (Figure 4). In particular, more than 50% 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, regardless of intercropping's frequency in crop sequences. Similar levels of self-sufficiency were achieved after incorporating the effects of N inputs and temporal niche differentiation (TND) on the pLERs (Supplementary Figure 10). Assuming a N fertilization rate of 148 $kg.ha^{-1}$ and pLERs values of 0.51 and 0.78 for soybean and maize, respectively, the potential self-sufficiency rates ranged from 47 to 86% 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. 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

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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).

In sensitivity analyses, 25% or 50% soybean self-sufficiency was reached as long as soybean pLER was higher than 0.3 and 0.31, respectively (Supplementary Figures 11-12). Our simulations suggest that as soybean pLER increases, higher maize pLER would be required to maintain high self-sufficiency levels for both crops. In an allocation scenario targeting 50% of soybean self-sufficiency, with a maize pLER of 0.79, full maize self-sufficiency would be achieved when soybean pLER remains lower than 0.41. However, when soybean pLER exceeds this threshold, maize self-sufficiency does not exceed 75% (Supplementary Figure 12). This reflects a trade-off: as intercropping becomes more efficient for soybean production (i.e., higher soybean pLER), less land is needed to meet the soybean self-sufficiency target. Because the intercropping area is lower, maize production in intercropping is reduced. Similar patterns were obtained when targeting 25%, 75% or 100% soybean self-sufficiency (Supplementary Figures 11, 13, and 14). For higher objectives, one limiting factor was the maximum area allocated to intercropping. While three-quarters of the EU's demand in soybean could be met with a relatively low soybean pLER of 0.46, achieving full soybean self-sufficiency using less than 25 million hectares would require a minimum pLER of 0.62 (Supplementary Figures 13-14).

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 15-16). 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 17). 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 18).

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 maize-soybean

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intercropping 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 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] If more productive intercropping scenarios (i.e., soybean pLER >0.5) 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 in the least productive intercropping scenario. In this study, intercropping's contribution to maize and soybean self-sufficiency slightly decreased with higher N inputs or stronger competition between maize and soybean, but still strongly improved the current levels in the EU. 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[31] 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,[32] particularly under increased nitrogen fertilization[22] and nutrients availability.[31] However, wider strip distance,[33] moderate maize planting density, or shorter growth periods' overlap[31] could contribute in reducing the competition between species in intercrops. In Europe, the performance of cereals-legumes mixtures is also affected by climate condition, especially rainfall, and farming practices such as tillage, and nature and quantity of applied fertilizers.[34] Given the limited information on the interaction between soybean productivity in intercropping and other farming practices in Europe, additional trials are required to refine maize-soybean intercropping performances and to help

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identifying the best combinations of field configuration, fertilization, and water management which maximizes the productivity of intercropping in the EU context.

Although several studies suggest that deploying intercropping in Europe could provide agroecological benefits while maintaining crop productivity,[35] its development is hampered by numerous barriers[36,37] throughout the food value chain, but predominantly faced by farmers.[38] Tackling only the farmer-specific barriers is necessary but insufficient to promote widespread adoption across the EU.[36,38] 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, 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.

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.[39] 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[40,41] and maize.[42] 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.[43,44] Overall, it has been shown soybean production in Europe is likely to increase under various climate change scenarios compared to historical conditions.[10,44] On the contrary, maize yields are expected to decline, with an estimated 10% loss per degree Celsius increase if no adaptation strategies are implemented.[42] 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.[42,45] 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

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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.[46,47] However, a 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,[48] 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.[10,41,49] 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

Data

For both soybean and maize, we built training datasets including gridded data on historical worldwide yields collected in major producing areas,[39] irrigated fraction from the SPAM2010 database,[50] 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.[51] Further details on data pre-processing steps are provided in Supplementary Material 3. The total number of sites (resp. number of site-year) included in the soybean and maize datasets reached 3,286 (116,516) and 2,064 (72,964), respectively. In producing sites, detrended yield 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 19). Mean (standard deviation) yield 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

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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.

Yield projections in the EU

Separate models were built 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 (Supplementary Material 4). The choice of the model was guided by previous works comparing various techniques to aggregate climate predictors and various algorithms to predict soybean yield.[10,40] 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 yield. Following this methodology, distinct predictive models were built for each crop. Variants of these models using different climate data aggregation methods (i.e., monthly average, seasonal average, or a higher number of PCs) were also developed 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). This approach was selected to predict the annual yields of rainfed soybean and maize in pure stands for each site-year in the EU over 2000-2023 using climate and irrigation data from the ERA5-Land database[51] and water management from the SPAM2010 database[50] 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 20).

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

The reference pLER values used in this study – 0.56 for soybean and 0.79 for maize – come 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 21-22). 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 less optimistic (i.e., lower pLER), preventing us to overestimate the potential contribution of intercropping. For each site this projection dataset, soybean production in intercropping was estimated by multiplying annual predicted soybean yield by the soybean pLER,[22] the cropland area in the site from the SASAM dataset,[52] and a coefficient representing the return frequency of intercropping in crop sequences (e.g., 1/4 for one-in-four frequency). To limit the risk of pests and diseases,[27,28] a one-in-four years frequency was

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considered, corresponding to allocating each year 25% of the cropland area in each site. Sites with yields <1 t.ha^{-1}, corresponding to the minimum yield observed in the US and Italy in the training dataset (Supplementary Figure 19) were considered as unsuitable conditions for soybean production and excluded. Maize production through intercropping was estimated following a similar procedure.

Over 2018-2022, 36.3 Mt soybean were on average consumed in the EU.[11]. The area required by intercropping to produce a target soybean production (P_S^*) covering 25%, 50%, 75%, or 100% of the average annual soybean consumption in the EU was estimated. For each self-sufficiency 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 a maximum threshold, chosen to limit competition with other crops. We supposed that the area allocated to soybean would not exceed 25 Mha, which corresponds to 25% of EU croplands in 2018[29] and to the area dedicated to wheat, which is currently the most cultivated crop in Europe (average 2018-2022).[53] 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 largest production of maize in the region of interest. Finally, 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

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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]

To evaluate the effects of high N inputs and temporal niche differentiation (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, we assumed a fertilization rate of 148 $kg.ha^{-1}$, corresponding to the 75th percentile of N dose applied on maize in the European Union (EU) members states in 2017-2018 according to the data of the International Fertilization Association.[30] This level of fertilization led to pLER values of 0.51 and 0.78 for soybean and maize, respectively. Second, we assumed that both species had 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 European Union.

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 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. All data analyzed in this paper are publicly available in associated publications, including maize and soybean historical yields,[39] water management,[50] and climate conditions.[51]

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Figures

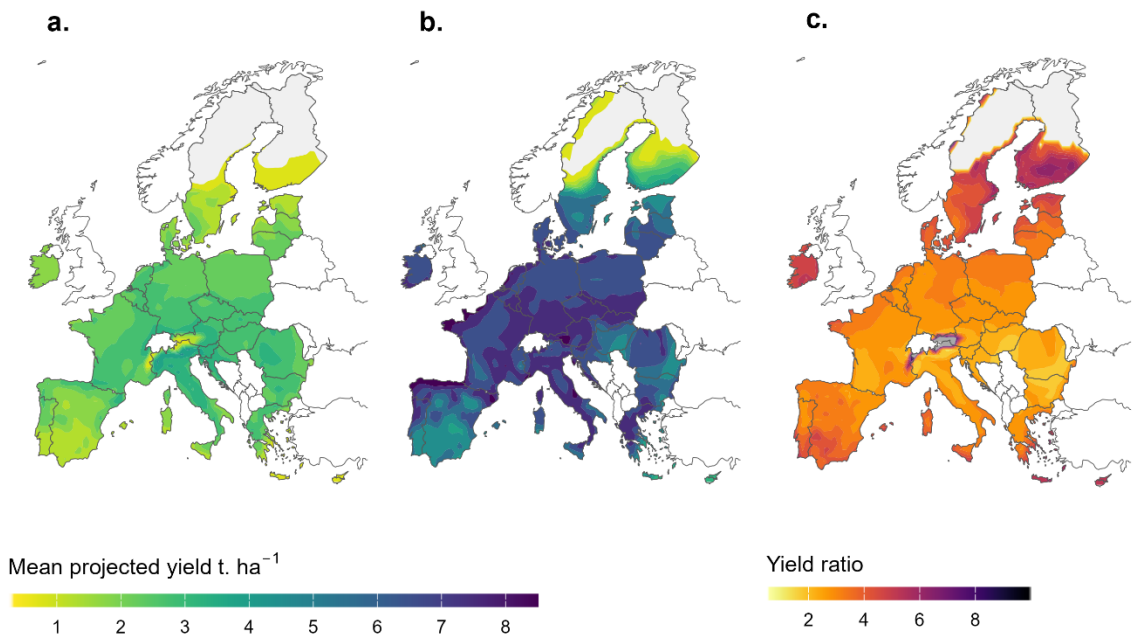

Figure 1. Soybean (a) and maize (b) rainfed yield projections (2000-2023 averages), and ratio maize/soybean (c) in the European Union. Projections were obtained from random forest models based on climate inputs (derived from the ERA5-land dataset) covering the crop growing seasons (April-November for 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), areas with average crop yield ~ 0 t.ha^{-1} are displayed in grey. For panel (c), the yield ratio was set to 0 in areas with very low maize and soybean yields (i.e., <0.5 t.ha^{-1}), and areas close to the Alps with low soybean yields (i.e., < 1 t.ha^{-1}) but moderate-to-high maize yields (i.e., > 6 t.ha^{-1}), characterized by the highest yield ratios, were indicated as dark grey.

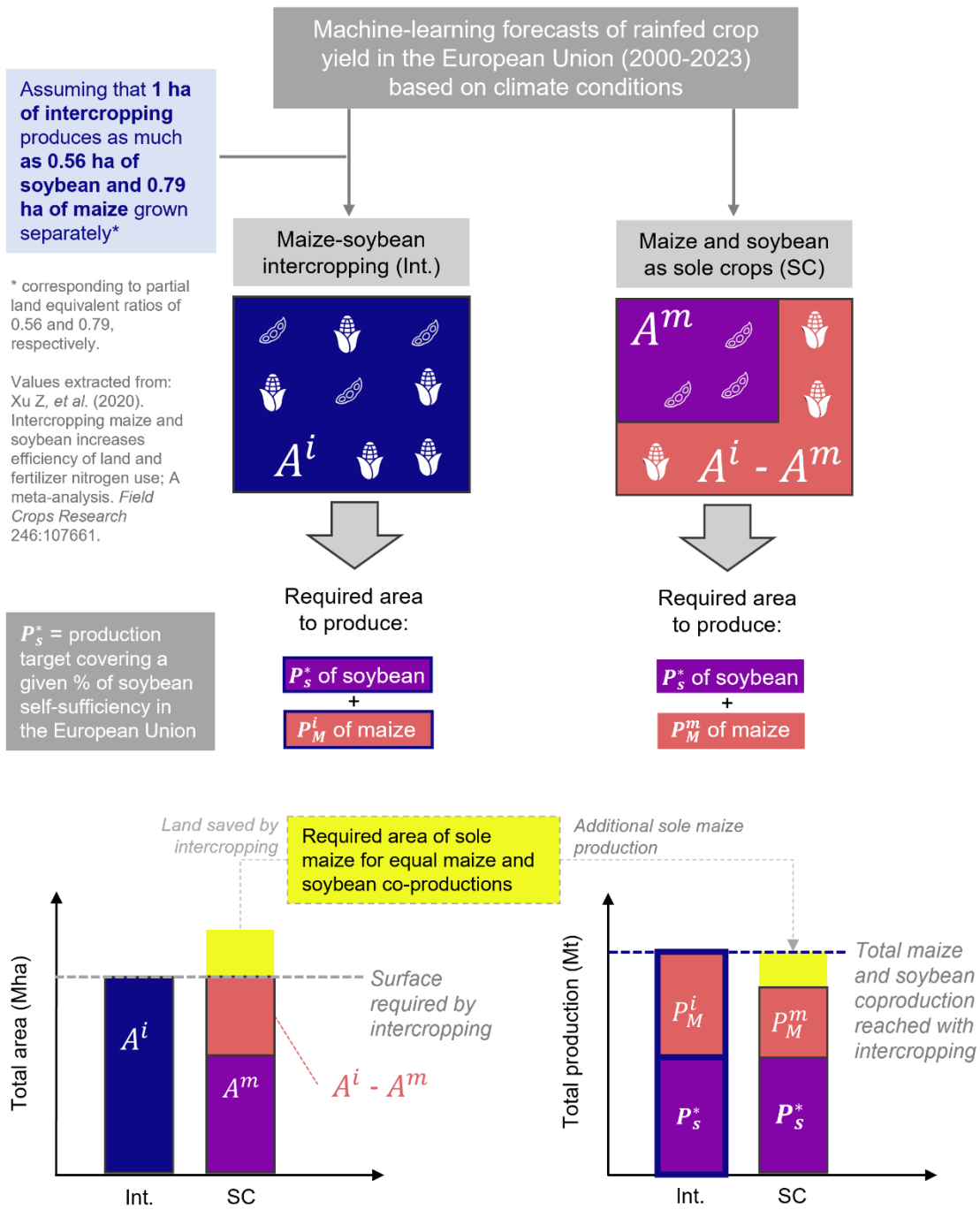

Figure 2. Procedure applied to estimate the area requirements under intercropping and sole cropping to meet a target soybean production (P_S^*) in the European Union, to compare the efficiency of both strategies in maximizing both soybean and maize coproduction, and to quantify the land saving allowed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

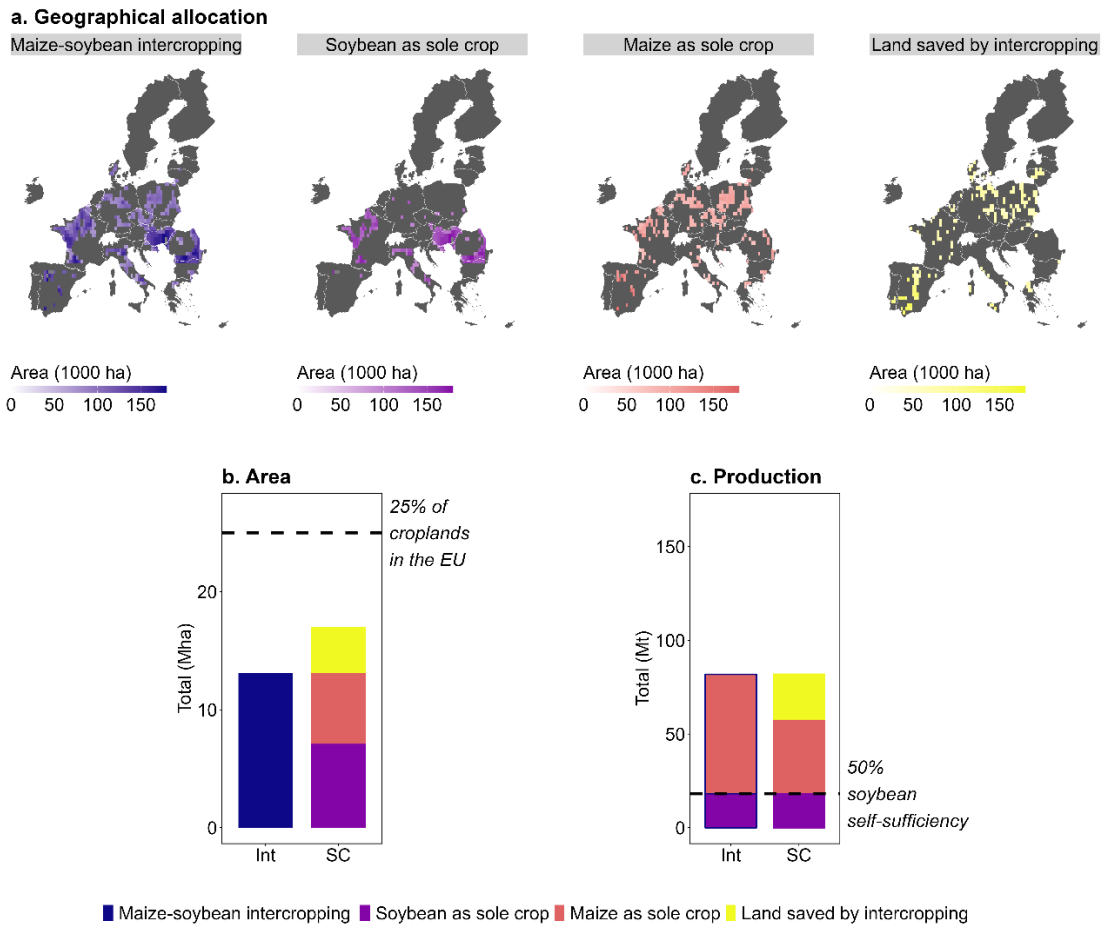

Figure 3. Comparison of maize-soybean intercropping (Int) and sole cropping (SC) for 50% soybean self-sufficiency in the European Union (EU). Maize-soybean intercropping was sequentially allocated in highest yielding sites, ranked by soybean productivity based on mean average production over 2000-2023 period in rainfed conditions, until 50% soybean self-sufficiency (i.e., 18.1 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. (left map) and with the SC (three maps on the right) strategies. 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).

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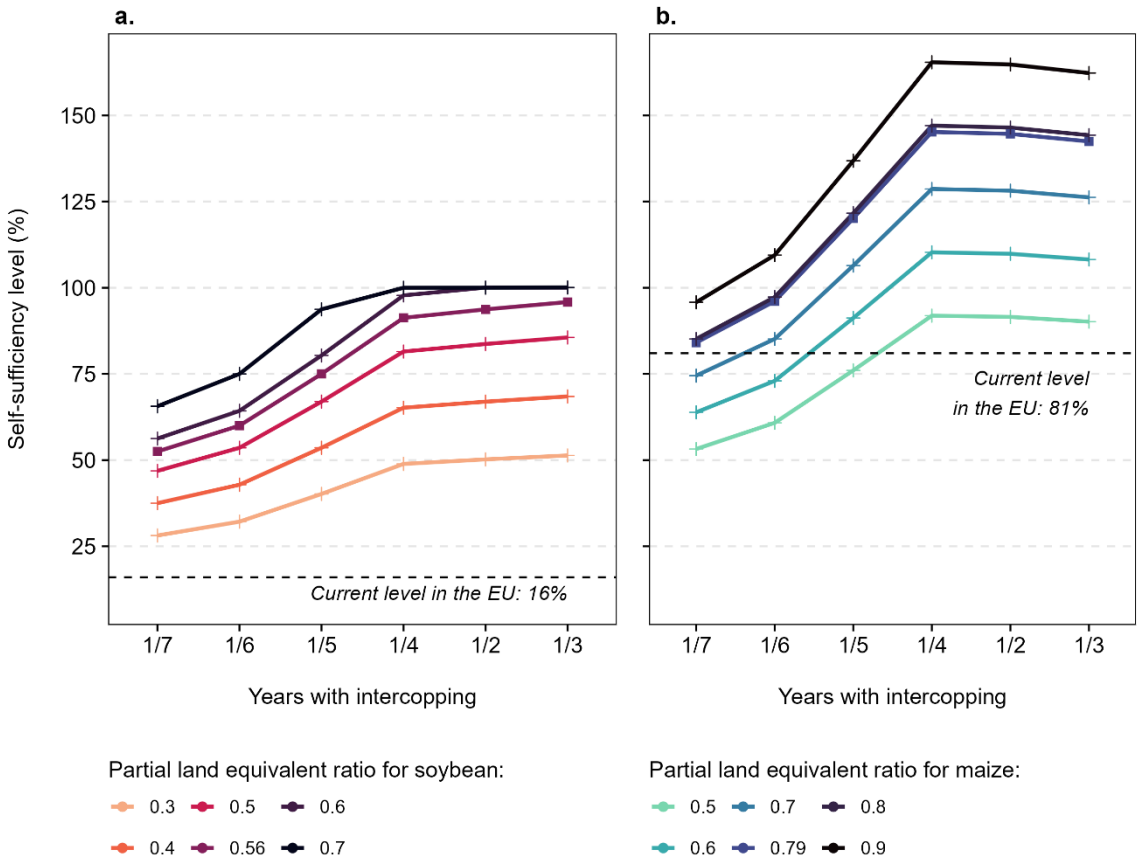

Figure 4. Levels of soybean (a) and maize (b) self-sufficiency in the European Union (EU) achieved from intercropping for different assumptions of partial land equivalent ratio (pLER) and crop return frequency.

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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