GRASSROOTS JOURNALS

Grassroots Journal of Natural Resources, Vol.9 No.2 (August 2026)
ISSN: 2581-6853 | CODEN: GJNRA9 | Published by The Grassroots Institute
Website: https://grassrootsjournals.org/gjnr | Main Indexing: WoS, CABELL, EBSCO

ISSN 2581-6853 | 9(2) August 2026

00653 | Research Article

Photosynthetic Dynamics and Yield Formation in Maize and Soybean under Sole Cropping and Binary Intercropping Systems

Volodymyr Mokriienko*[1], Svitlana Kalenska[2]

[1]Department of Plant Science, National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine. E-mail: mokrienko@ukr.net | ORCID: https://orcid.org/0000-0002-5604-442X

[2]Department of Plant Science, National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine. E-mail: kalenskaya@nubip.edu.ua | ORCID: https://orcid.org/0000-0002-3392-837X

**Corresponding Author*

How to cite this paper: Mokriienko, V. and Kalenska, S. (2026). Photosynthetic Dynamics and Yield Formation in Maize and Soybean under Sole Cropping and Binary Intercropping Systems. *Grassroots Journal of Natural Resources*, 9(2): 60-77. Doi: https://doi.org/10.33002/nr2581.6853.090206

Received: 17 March 2026
Reviewed: 21 April 2026
Provisionally Accepted: 27 April 2026
Revised: 16 July 2026
Finally Accepted: 22 July 2026
Published: 31 August 2026
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Abstract

The present study aimed to quantify how the photosynthetic apparatus of maize and soybean is reorganized under binary intercropping and to establish how that reorganization translates into yield formation under contrasting fertilization regimes in the Forest-Steppe zone of Ukraine. A five-year field experiment (2021–2025) was carried out on typical low-humus chernozem in the Right-Bank Forest-Steppe as a two-factor split-plot design with four replications. Factor A comprised five cropping systems, namely sole maize (hybrid RZhT Zanetikks, FAO 340), sole soybean (cultivars Sireliya and Sakuza) and two binary maize–soybean intercrops established in an additive arrangement with soybean at 50% of its sole-crop seeding rate. Factor B comprised three fertilization regimes, namely an unfertilized control, $N_{60}P_{45}K_{45}$ and $N_{90}P_{60}K_{60}$. Leaf area index (LAI), photosynthetic potential (PP), net assimilation rate (NAR), grain yield, land equivalent ratio (LER) and stability parameters were determined. Binary intercrops reached a maximum canopy LAI of 6.56–6.81, which exceeded sole maize by 44–50% and sole soybean by 78–85%. Photosynthetic potential attained 4.00–4.32 million $m^2 \cdot$days ha^{-1}, or 43–54% above sole maize, and canopy NAR reached 8.63–10.78 g m^{-2} d^{-1}. Total intercrop grain yield of 9.92–15.13 t ha^{-1} exceeded sole maize by 36–45%, and the maize component alone yielded 11.5–19.1% more in the intercrop than in sole cropping at identical maize density. Partial LER for maize was consistently above unity (1.12–1.19), which provides a formal, design-independent quantification of facilitation, while total LER ranged from 1.89 to 2.15. Agronomic efficiency of the intercrop was 59.5–61.5 kg grain per kg N at $N_{60}P_{45}K_{45}$ and declined at the higher rate. The intercrop gross margin was 63–91% above sole maize. Increasing fertilization from $N_{60}P_{45}K_{45}$ to $N_{90}P_{60}K_{60}$ gave a VCR of only 1.79–1.83, supporting $N_{60}P_{45}K_{45}$ as the more efficient tested rate.

Keywords

Binary intercropping; Forest-Steppe of Ukraine; Gross margin; Land equivalent ratio; Leaf area index; Net assimilation rate; Photosynthetic potential; Yield stability

Introduction

Global food security depends on cropping systems that raise output per unit of land while limiting the environmental cost of that output (Foley *et al.*, 2011; Tilman *et al.*, 2011). Intercropping, the simultaneous cultivation of two or more species on the same field, is a long-established route to this goal that has regained scientific attention because it can deliver yield gains without proportional increases in external inputs (Brooker *et al.*, 2015; Li *et al.*, 2020). The pairing of maize (*Zea mays* L.) with soybean (*Glycine max* (L.) Merr.) is agronomically attractive because the two species differ in photosynthetic pathway, canopy height, root architecture and nitrogen acquisition strategy, and these differences create scope for temporal and spatial niche differentiation, for facilitation through biological nitrogen fixation and for improved resource-use efficiency (Andrade *et al.*, 2017; Bedoussac *et al.*, 2015; Hauggaard-Nielsen and Jensen, 2005; Martin-Guay *et al.*, 2018).

The photosynthetic apparatus is the proximate determinant of agrocenosis productivity. Leaf area index sets the fraction of photosynthetically active radiation that a canopy can intercept, photosynthetic potential integrates leaf area with its functional duration over the season, and net assimilation rate expresses how efficiently intercepted energy is converted into dry matter (Gou *et al.*, 2016; Zhu, Long and Ort, 2010). In an intercrop, these three quantities are not simply the sum of the component crops, because vertical stratification alters both the size of the assimilatory surface and the light environment in which it operates. Recent work has begun to separate these two contributions. Chen *et al.* (2025) found that the yield advantage of soybean–maize intercropping in semi-arid China arose mainly through an enlarged leaf area index rather than through improved leaf-level photosynthetic parameters, whereas Nasar *et al.* (2023) attributed a 30–34% maize yield gain under intercropping to enhanced nitrogen assimilatory enzyme activity. Which of these routes predominates under a given edaphoclimatic regime remains open, and the answer has direct consequences for how such systems should be fertilized.

The Forest-Steppe zone of Ukraine is a demanding test case. Its deep chernozems support high baseline productivity, yet its semi-continental climate is becoming more variable, and projections indicate rising drought frequency and more frequent temperature extremes (Prysiazhniuk *et al.*, 2023; Shvidenko *et al.*, 2017). Systems that combine high absolute output with buffered interannual variability are therefore of particular regional value. Global evidence on maize–soybean intercropping is nevertheless dominated by East Asian relay-strip systems and by semi-arid irrigated environments (Du *et al.*, 2018; Raza *et al.*, 2022; Xu *et al.*, 2020), and multi-year datasets that follow the photosynthetic apparatus and the yield response through the same experiment are scarce for temperate rainfed chernozem. The specific gap addressed here is the absence of a multi-season, quantitatively integrated account linking canopy-level photosynthetic parameters, land-use efficiency and interannual yield stability in maize–soybean intercropping on rainfed chernozem of the Ukrainian Forest-Steppe.

The present study aimed to evaluate the photosynthetic parameters of maize and soybean grown in sole and binary intercropping systems under three fertilization regimes, and to determine how those parameters shape yield formation, yield structure, land-use efficiency and yield stability over five consecutive seasons.

Materials and Methods

Study area and soil

The experiment was conducted from 2021 to 2025 in a stationary field trial at the Agronomic Research Station of the National University of Life and Environmental Sciences of Ukraine (50°05′21.2″N, 30°12′44.2″E; village of Pshenychne, Vasylkiv district, Kyiv region) in the central part of the Right-Bank Forest-Steppe zone. The climate is moderately continental, with a mean annual temperature of 7.5–8.0 °C, mean annual precipitation of 550–600 mm and growing-season (April–September) precipitation of 350–400 mm. The hydrothermal coefficient over the study period ranged from 0.85 in the dry season of 2022 to 1.42 in the favorable season of 2023, with a five-year mean of 1.12, which is typical for the zone.

The soil is a typical low-humus chernozem of medium loamy texture developed on loess, corresponding to a Haplic Chernozem in the international classification (FAO, 2015). The humus horizon extends to 25–30 cm. Soil samples were taken from the 0–30 cm layer before sowing in each season. Humus content was determined by the Tyurin wet-oxidation method with $K_2Cr_2O_7$ in H_2SO_4, alkaline-hydrolysable nitrogen by the Kornfield method, available phosphorus and exchangeable potassium by the Chirikov method with extraction in 0.5 M CH_3COOH, and pH potentiometrically in a 1 M KCl suspension. Initial characteristics of the 0–30 cm layer were 3.5 ± 0.2% humus, 112 ± 8 mg kg^{-1} alkaline-hydrolysable nitrogen, 128 ± 12 mg kg^{-1} available P_2O_5, 118 ± 10 mg kg^{-1} exchangeable K_2O and pH(KCl) 6.2 ± 0.3.

Experimental design, spatial arrangement and crop management

The trial was established as a two-factor split-plot design in randomized complete blocks with four replications. Main plots carried Factor A, the cropping system, at five levels, and subplots carried Factor B, the fertilization regime, at three levels (Table 1). Individual subplot area was 50 m^2 (5 × 10 m), and 1 m buffer strips separated adjacent plots. All rows ran north to south, so that both components of the intercrop received comparable diurnal radiation exposure.

Maize was sown at 70,000 viable seeds ha^{-1} in rows spaced 70 cm apart, giving an in-row plant-to-plant distance of approximately 20 cm, at a depth of 4–5 cm. Sole soybean was sown at 450,000 viable seeds ha^{-1} in rows spaced 35 cm apart, giving an in-row distance of approximately 6 cm, at a depth of 2–3 cm. The binary systems used an additive arrangement in which maize retained its full sole-crop density and spatial layout, and a single soybean row was inserted midway between adjacent maize rows, that is, 35 cm from each maize row. Soybeans in the intercrop were sown at 225,000 viable seeds ha^{-1}, which is 50% of its sole-crop rate, giving an in-row distance of approximately 13 cm. Because maize density was unchanged and soybean was added rather than substituted, the intercrop's total plant population exceeded that of sole maize. This design choice is noted here because it governs how the land equivalent ratio is interpreted in Section 4.2.

Winter wheat was the preceding crop in every season. Primary tillage comprised stubble disking to 10–12 cm followed by moldboard plowing to 25–27 cm. Compound fertilizer FERTIS NPK 10-20-20+S+ME was incorporated during primary tillage according to the design, and the balance of nitrogen was applied as ammonium nitrate (34.4% N) during pre-sowing cultivation. Fertilizer rates are expressed as kg ha^{-1} of active ingredient and were applied per unit of total plot area, identically in sole and intercropped plots. Crop protection followed standard practice, with pre-emergence and post-emergence herbicide application and insecticide treatment triggered by scouting thresholds. Each subplot was harvested at full physiological maturity of the respective component. The two outermost rows and 0.5 m at each plot end were treated as borders and excluded from harvest, so that all reported yields derive from the inner harvest area of 30.8 m^2. Yields were adjusted to standard moisture content of 14% for maize and 13% for soybean.

Table 1: Experimental design. Factor A, cropping system

No.	*Cropping system*	*Cultivar or hybrid*	*FAO / CHU*	*Seeding rate, thousand viable seeds ha^{-1}*
1	Sole maize	RZhT Zanetikks	FAO 340	70
2	Sole soybean	Sireliya	CHU 2300	450
3	Sole soybean	Sakuza	CHU 2600	450
4	Binary intercrop	RZhT Zanetikks + Sireliya	—	70 + 225
5	Binary intercrop	RZhT Zanetikks + Sakuza	—	70 + 225

Factor B, fertilization (kg ha^{-1} of active ingredient), comprised an unfertilized control, $N_{60}P_{45}K_{45}$ and $N_{90}P_{60}K_{60}$.

Photosynthetic parameters and their definitions

Four canopy parameters were used throughout, and each is defined once here in order to avoid ambiguity. Unless a value is explicitly qualified as “per plant”, every value reported in this paper is expressed per unit of total ground area of the plot. Component values given for maize or soybean within an intercrop are therefore also per unit of total intercrop area, not per unit of the strip occupied by that component, and the canopy value of an intercrop is the arithmetic sum of its two component values.

Leaf area index (LAI, m^2 m^{-2}) is the ratio of one-sided leaf area to ground area. *Photosynthetic potential* (PP, million m^2·days ha^{-1}) is the time integral of leaf area over the growing season and is numerically identical to leaf area duration; the term photosynthetic potential is retained here for consistency with the regional agronomic literature. *Net assimilation rate* (NAR, g m^{-2} d^{-1}) is the increment in total above-ground dry matter per unit leaf area per unit time between consecutive sampling dates; this quantity is termed net photosynthetic productivity in part of the older literature, and the two designations are used synonymously. The abbreviation NPR is not used in this paper. *Photosynthetic potential use efficiency* (kg per thousand m^2·days) is grain yield divided by seasonal PP.

Leaf area was measured on five common sampling dates defined by maize development: 7-leaf, 15-leaf, silking (concurrent with soybean flowering), milk and wax maturity. At the first sampling date, soybean was at the third trifoliate stage; this term is used consistently throughout the manuscript. At each stage, ten representative plants of each component were sampled per plot. Individual leaf area was computed by the length × width × correction-factor method, with k = 0.67 for maize leaves and k = 0.72 for soybean trifoliates, and was verified against planimetric measurement with a LI-3100C Area Meter (LI-COR Biosciences, Lincoln, NE, USA) on a subset of 50 leaves per treatment. Leaf area per hectare was obtained by multiplying mean leaf area per plant by the actual stand density recorded in that plot. Photosynthetic potential was obtained by trapezoidal integration of the leaf area dynamics over the season.

Yield and yield structure

At harvest maturity, 25 representative plants of each component were collected per plot. For maize, ear length and diameter, number of kernel rows per ear, kernels per row, total kernels per ear, shelling percentage and 1000-kernel weight were recorded. For soybean, productive nodes per plant, pods per plant, seeds per pod, total seeds per plant, seed mass per plant and 1000-seed weight were recorded. Grain protein content was determined by the Kjeldahl method (AOAC 2001.11) and starch content by the Ewers polarimetric method. All determinations were made independently on each of the four replications.

Derived indices

Partial and total land equivalent ratios were computed as
$LER_{maize} = Y_{im} / Y_{sm}$, $LER_{soybean} = Y_{is} / Y_{ss}$, $LER = LER_{maize} + LER_{soybean}$,
where Y_{im} and Y_{is} are the grain yields of the maize and soybean components of the intercrop per unit of total intercrop area, and Y_{sm} and Y_{ss} are the corresponding sole-crop yields. Because the design is additive rather than substitutive, total LER values obtained here are not directly comparable with values from replacement designs, and this restriction is applied consistently in the Discussion.

Agronomic efficiency of fertilization was computed as
$AE = (Y_F - Y_0) \times 1000 / N_{applied}$,
expressed as kg of grain per kg of applied nitrogen, where Y_F and Y_0 are the system yields of the fertilized and unfertilized treatments in t ha^{-1} and $N_{applied}$ is the nitrogen rate in kg ha^{-1}. For intercrops, Y refers to the total yield of both components.

An indicative partial budget was constructed for each treatment. Gross margin was computed as the value of the grain harvested minus those variable costs that differ among the systems compared, namely mineral fertilizer, seed of both components, inoculant and the additional harvest pass required by the intercrop. Costs common to all treatments, such as tillage, crop protection and land, were excluded because they do not affect the ranking. Prices were taken as of mid-2026 for the Kyiv region at 9,200 UAH t^{-1} for maize grain and 19,400 UAH t^{-1} for soybean seed on an EXW elevator basis, 31 UAH kg^{-1} for ammonium nitrate containing 34.4% N and 33 UAH kg^{-1} for complex NPK 10-20-20, with maize seed at 4,800 UAH ha^{-1}, certified soybean seed at 40 UAH kg^{-1}, inoculant at 300 UAH ha^{-1} and the additional harvest pass at 2,000 UAH ha^{-1}. The value-

cost ratio (VCR) for moving from the moderate to the intensive fertilization regime was computed as the ratio of additional revenue to additional variable cost; the corresponding change in gross margin was reported separately. Sensitivity of the conclusions to the soybean-to-maize price ratio and to the fertilizer price level was tested by recomputing the budget across a range of values.

Interannual stability was characterized by the coefficient of variation, $CV = 100 \cdot s / \bar{y}$, where s is the standard deviation and $\bar{y}$ the mean of the five annual yields, by the yield stability index, $S_i = Y_{min} / Y_{max}$; and by the parameters of the Eberhart and Russell (1966) model, namely the regression coefficient b_i of treatment yield on the environmental index of each season and the deviation from regression S^2d_i.

Statistical analysis

Data were analyzed by mixed-model analysis of variance appropriate to a split-plot design repeated over five seasons. Cropping system (A), fertilization (B) and their interaction (A × B) were treated as fixed effects. Season, replication nested within season, and the main-plot error term of cropping system within replication and season were treated as random effects, and the season × treatment interactions were tested against the appropriate random error. The full fixed part of the model was $Y_{ijk} = \mu + A_i + B_j + (AB)_{ij} + \varepsilon_{ijk}$, fitted separately for each measured trait.

Least significant differences at $p = 0.05$ were derived as $LSD_{0.05} = t_{0.05,\,df} \cdot \sqrt{(2 \cdot MS_E / n)}$, where MS_E is the error mean square of the stratum against which the comparison is made, df its degrees of freedom, and $n = 4$ the number of replications. Subplot comparisons within a main plot, main-plot comparisons and comparisons across both factors therefore use different error terms, and the $LSD_{0.05}$ reported at the foot of each table is the value applicable to comparisons among the treatment means presented in that table. Each results table therefore reports four least significant differences, namely one for comparisons among individual treatment means, one for the marginal means of cropping system, one for the marginal means of fertilization and one for the interaction. Two means differ significantly at $p = 0.05$ when the absolute difference between them exceeds the relevant $LSD_{0.05}$.

Pearson correlation coefficients were computed between photosynthetic parameters and yield components, and their significance was tested by a two-tailed t-test with $n - 2$ degrees of freedom. The relationship between grain yield and seasonal photosynthetic potential was described by least-squares linear regression, with the coefficient of determination reported. All computations were performed in Statistica 10 following the procedures set out by Prysiazhniuk *et al.* (2016), and phenological staging followed Prysiazhniuk *et al.* (2024).

Results

Leaf area index

At the 7-leaf stage sole maize had formed 5.24 thousand m^2 ha^{-1} of leaf area in the unfertilized control, corresponding to LAI = 0.52, which is typical of early growth before

canopy closure (Fig. 1). Mean daily leaf area increment over the 7-leaf to 15-leaf interval was 0.52–0.62 thousand m^2 ha^{-1} d^{-1}, and nitrogen use efficiency for leaf formation was 58–62 cm^2 g^{-1} N.

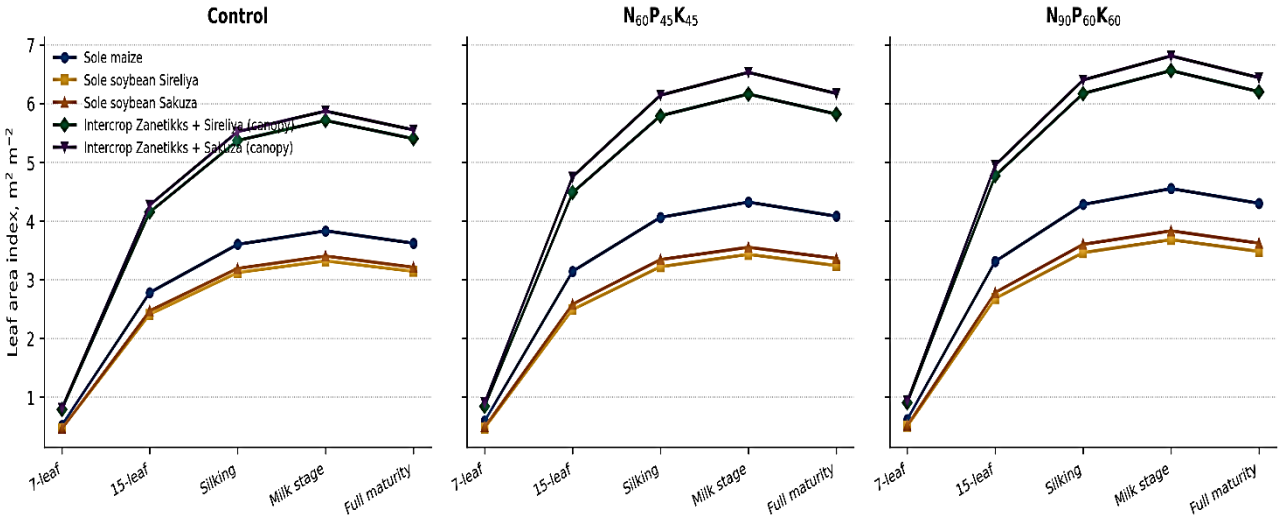

Figure 1: Seasonal course of leaf area index of maize and soybean in sole and intercropped stands under three fertilization regimes (means for 2021–2025). Values for the intercrops are canopy totals, that is, the sum of the maize and soybean components per unit of total ground area. Leaf area reached its seasonal maximum around silking, at 36.0 thousand m^2 ha^{-1} (LAI = 3.60) in the control and 42.8 thousand m^2 ha^{-1} (LAI = 4.28) under $N_{90}P_{60}K_{60}$. A further small gain of 6.3–6.4% occurred by the milk stage, when absolute maxima of 38.3–45.5 thousand m^2 ha^{-1} were recorded, and LAI reached 3.83–4.55, approaching the upper limit of the range generally regarded as optimal for sole maize.

Soybean formed consistently less leaf area than maize. At the third trifoliate stage, which coincides with the maize 7-leaf stage, cultivar Sireliya reached 4.56 thousand m^2 ha^{-1} (LAI = 0.46), or 13.0% below maize, and cultivar Sakuza reached a marginally higher 4.64 thousand m^2 ha^{-1}. Maximum soybean leaf area occurred at flowering, at 31.2–31.9 thousand m^2 ha^{-1} in the control and 34.6–36.0 thousand m^2 ha^{-1} under intensive fertilization, giving an LAI of 3.12–3.60 and an estimated interception of 85–90% of incident photosynthetically active radiation. The soybean response to fertilizer was weaker than that of maize, with leaf area gains of 3.1–4.7% under $N_{60}P_{45}K_{45}$ and 10.5–12.9% under $N_{90}P_{60}K_{60}$, which is consistent with the capacity of the crop to meet a large share of its nitrogen requirement symbiotically.

Within the binary intercrops, maize leaf area was slightly below its sole-crop level early in the season, at 4.97–5.01 thousand m^2 ha^{-1} at the 7-leaf stage, a shortfall of 4.4–5.2% that most likely reflects early competition for soil resources. The relative shortfall did not widen thereafter. At the 15-leaf stage, maize in the intercrop reached 26.4–26.5 thousand m^2 ha^{-1} (−4.7 to −5.0%), at flowering 34.1–34.3 thousand m^2 ha^{-1} (−4.7 to −5.3%), and at the milk stage 36.3–36.5 thousand m^2 ha^{-1} (−4.7 to −5.2%), and under fertilization the gap narrowed to 3.5–7.0%. The intercropped soybean component, sown

at half its sole-crop density, formed 2.83–3.08 thousand m^2 ha^{-1} at the third trifoliate stage, 62.1–66.4% of the sole-crop value per unit ground area, but 24–33% more leaf area per individual plant. Its seasonal maxima of 19.4–22.4 thousand m^2 ha^{-1} at flowering and 20.6–24.2 thousand m^2 ha^{-1} at the milk stage likewise represented 62.2–65.9% of sole cropping, in close proportion to the density reduction, and the component LAI of 1.94–2.42 lay below the sole-crop optimum while benefiting from improved illumination in the stratified canopy.

Summed over both components, the intercrop canopy was substantially larger than either sole crop. At the 15-leaf sampling stage, total leaf area in the unfertilized control was 41.5 thousand m2 ha−1 for the combination with Sireliya and 42.7 thousand m2 ha−1 for the combination with Sakuza. Compared at this same sampling date with sole maize (27.8 thousand m2 ha−1), these values were 49.3–53.5% higher; they were also 72.2–73.1% above the respective sole-soybean canopies. Under $N_{90}P_{60}K_{60}$ the canopy reached 61.7–64.0 thousand m^2 ha^{-1} at flowering, or 44.2–49.8% above sole maize, with a canopy LAI of 6.17–6.40, and attained its seasonal maximum of 65.6–68.1 thousand m^2 ha^{-1} at the milk stage, corresponding to a canopy LAI of 6.56–6.81 and to an estimated interception of 95–97% of incident radiation. Canopy LAI values of this magnitude exceed the optimum reported for sole stands, yet the correlation between yield and LAI was tighter in the intercrops ($r = 0.78–0.82$, $p < 0.01$) than in the sole crops ($r = 0.65–0.72$, $p < 0.05$), which indicates that the additional leaf area remained functionally productive rather than merely self-shading.

Photosynthetic potential

Over the 7-leaf to 15-leaf interval, the photosynthetic potential of sole maize was 0.25 million m^2·days ha^{-1} in the control, the modest value reflecting the short 17-day duration of the interval despite rapid leaf expansion, and fertilization raised it to 0.28–0.29 million m^2·days ha^{-1}. Seasonal PP of sole maize was 2.22 million m^2·days ha^{-1} in the control, rising to 2.57 million m^2·days ha^{-1} under $N_{60}P_{45}K_{45}$ (+15.8%) and to 2.80 million m^2·days ha^{-1} under $N_{90}P_{60}K_{60}$ (+26.1%), driven jointly by an 18.5–19.0% larger leaf area and a 5–7 day longer period of green leaf retention (Figure 2).

Soybean distributed its PP differently across the season. The interval from the milk stage to full maturity contributed 1.26–1.86 million m^2·days ha^{-1}, or 79.7–82.3% of the seasonal total, reflecting prolonged leaf retention over the 39–50 days of pod filling and ripening, whereas the budding-to-flowering interval contributed 0.97–1.34 million m^2·days ha^{-1} and the short 11–14 day flowering interval only 0.35–0.56 million m^2·days ha^{-1}.

The internal structure of the maize photosynthetic potential is shown in Fig. 3. The interval from the 15-leaf stage to silking made the largest single contribution in every treatment, at 0.79–1.13 million m^2·days ha^{-1} or 36–38% of the seasonal total, and it was also the interval that responded most strongly to fertilizations. The opening interval from the 7-leaf to the 15-leaf stage contributed only 0.24–0.29 million m^2·days ha^{-1} despite the exponential leaf expansion occurring within it, because the interval itself lasts only 17 days.

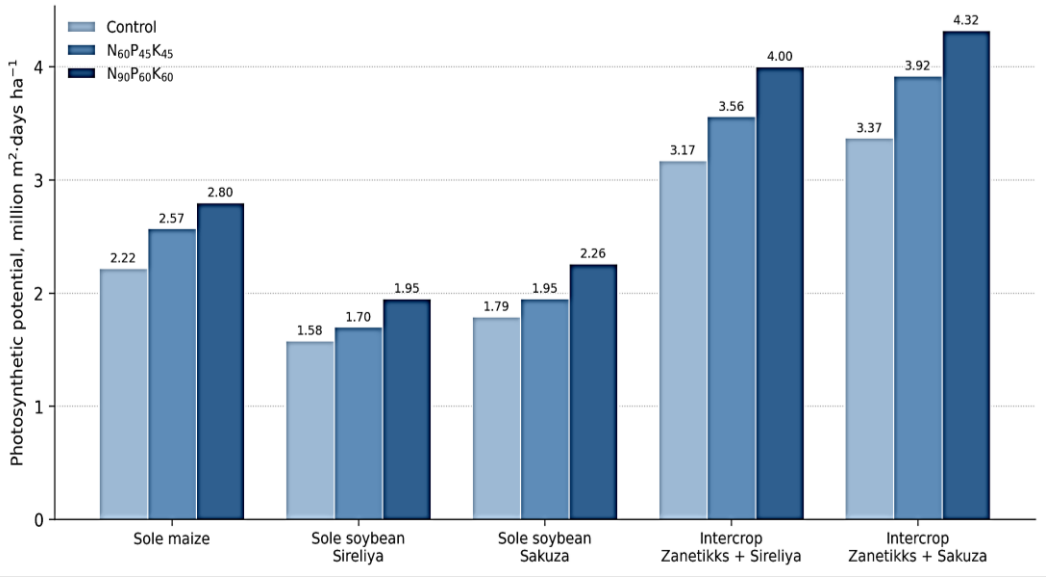

Figure 2: Seasonal photosynthetic potential of the cropping systems under three fertilization regimes (means for 2021–2025).

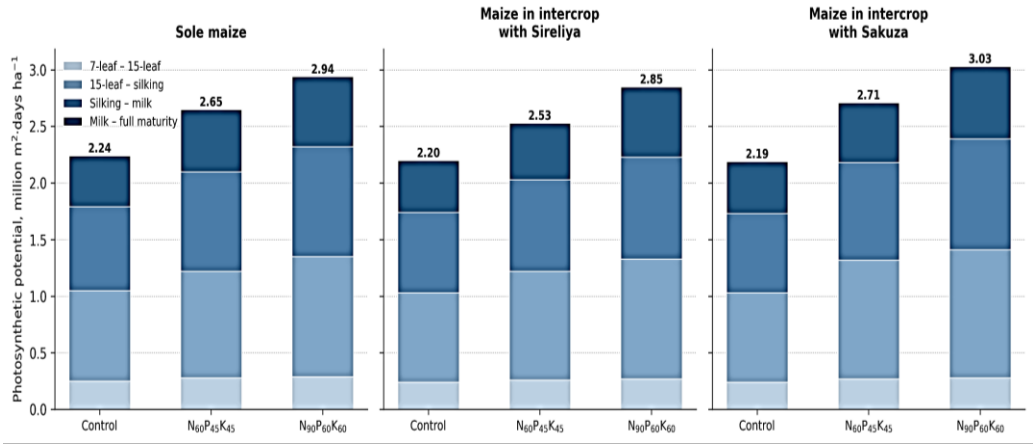

Figure 3: Contribution of successive phenological intervals to the seasonal photosynthetic potential of maize in sole and intercropped stands (means for 2021–2025). Stack totals are the sums of the interval values and differ from the tabulated seasonal totals by up to 5% through rounding of the interval estimates.

The maize component of the intercrops accumulated 2.14–2.15 million m^2·days ha^{-1} in the control, 3.2–3.6% below sole cropping, and the difference narrowed under fertilization to 2.42–2.60 million m^2·days ha^{-1} (−5.8 to −0.8%) at $N_{60}P_{45}K_{45}$ and to 2.66–2.81 million m^2·days ha^{-1} (−5.0 to +0.4%) at $N_{90}P_{60}K_{60}$. The intercropped soybean component reached 1.02–1.23 million m^2·days ha^{-1} in the control, or 64.6–68.7% of the sole-crop value per unit ground area, again broadly proportional to the halved density, while on a per-plant basis PP was 29.1–37.4% higher than in sole cropping. Canopy PP of the intercrops was correspondingly high, at 3.17–3.37 million m^2·days ha^{-1} in the control, which exceeded sole maize by 42.8–51.8% and sole soybean by a factor of 1.9–

2.1, rising to 3.56–3.92 million m^2·days ha^{-1} under $N_{60}P_{45}K_{45}$ and to 4.00–4.32 million m^2·days ha^{-1} under $N_{90}P_{60}K_{60}$ (+42.9 to +54.3% relative to sole maize). The highest value, 4.32 million m^2·days ha^{-1}, occurred in the RZhT Zanetikks + Sakuza combination under intensive fertilization, where peak leaf area of the two components was most closely synchronized.

Efficiency of PP conversion into grain was also higher in the intercrops, at 3.00–3.13 kg per thousand m^2·days in the control and 3.50–3.82 kg per thousand m^2·days under fertilization, which indicates that the enlarged assimilatory surface was matched by adequate sink capacity. Correlation analysis identified different critical periods for the two species. For maize, the strongest association with yield was PP accumulated between the 15-leaf stage and flowering ($r = 0.82–0.85$, $p < 0.01$), where each additional 0.1 million m^2·days ha^{-1} corresponded to 0.95–1.12 t ha^{-1} of grain. For soybean, the critical interval was from the milk stage to full maturity ($r = 0.78–0.81$, $p < 0.01$), where the same PP increment corresponded to 0.18–0.22 t ha^{-1} of seed. In the intercrops, the combined contribution of the period-specific PP terms exceeded the sum of the corresponding sole-crop contributions by 15–18%, which is consistent with an altered partitioning of assimilates between the components rather than with simple additivity.

Net assimilation rate

Sole maize reached its highest net assimilation rate between the 15-leaf stage and silking, at 6.01 g m^{-2} d^{-1} in the control, when high irradiance, favorable temperature and adequate water supply coincide and the C_4 pathway operates with minimal photorespiration (Table 2). Fertilization raised NAR to 6.57 g m^{-2} d^{-1} under $N_{60}P_{45}K_{45}$, whereas under $N_{90}P_{60}K_{60}$ it fell slightly to 6.46 g m^{-2} d^{-1}, which is attributable to excessive vegetative growth and increased mutual shading at the higher nitrogen rate. During grain filling NAR declined to 4.57–5.02 g m^{-2} d^{-1} as assimilates were redirected to reproductive organs and respiration increased, and over the final interval to full maturity it fell further to 3.93–4.14 g m^{-2} d^{-1} with leaf senescence and declining chlorophyll content, while remaining positive throughout.

Table 2: Net assimilation rate of maize and soybean in sole and binary stands, g m^{-2} d^{-1} (five-year means, 2021–2025)

Cultivar or hybrid	*Fertilisation*	*15-leaf – silking*	*Silking – milk stage*	*Milk stage – full maturity*
RZhT Zanetikks (sole)	Control	6.01	4.57	3.93
	$N_{60}P_{45}K_{45}$	6.57	4.94	4.14
	$N_{90}P_{60}K_{60}$	6.46	5.02	4.07
Sireliya (sole)	Control	1.53	2.95	0.43
	$N_{60}P_{45}K_{45}$	2.10	3.93	0.61
	$N_{90}P_{60}K_{60}$	1.50	2.61	0.45
Sakuza (sole)	Control	1.65	3.01	0.40
	$N_{60}P_{45}K_{45}$	2.05	3.64	0.51
	$N_{90}P_{60}K_{60}$	1.30	2.20	0.35
Zanetikks + Sireliya, maize component	Control	6.77	5.31	4.28
	$N_{60}P_{45}K_{45}$	7.55	6.35	5.30
	$N_{90}P_{60}K_{60}$	7.75	6.39	4.88

Cultivar or hybrid	*Fertilisation*	*15-leaf – silking*	*Silking – milk stage*	*Milk stage – full maturity*
Zanetikks + Sireliya, soybean component	Control	1.93	3.52	0.53
	$N_{60}P_{45}K_{45}$	2.49	4.43	0.69
	$N_{90}P_{60}K_{60}$	1.88	2.98	0.53
Zanetikks + Sireliya, canopy total	Control	8.70	8.83	4.81
	$N_{60}P_{45}K_{45}$	10.04	10.78	5.99
	$N_{90}P_{60}K_{60}$	9.63	9.38	5.41
Zanetikks + Sakuza, maize component	Control	6.80	5.37	4.30
	$N_{60}P_{45}K_{45}$	6.96	6.03	5.04
	$N_{90}P_{60}K_{60}$	7.16	5.88	4.65
Zanetikks + Sakuza, soybean component	Control	1.83	3.02	0.46
	$N_{60}P_{45}K_{45}$	2.25	3.84	0.63
	$N_{90}P_{60}K_{60}$	1.81	2.74	0.50
Zanetikks + Sakuza, canopy total	Control	8.63	8.39	4.76
	$N_{60}P_{45}K_{45}$	9.21	9.87	5.67
	$N_{90}P_{60}K_{60}$	8.97	8.63	5.15
$LSD_{0.05}$, individual means		0.12	0.10	0.13

All values are expressed per unit of total ground area. Component rows give the contribution of one species within the intercrop; canopy total rows are the sum of the two component rows. The graphical summary of this table is given in figure 4.

Canopy NAR of the intercrops exceeded that of either sole crop throughout the season. Between the 15-leaf stage and silking, the canopy reached 8.63–8.70 g m^{-2} d^{-1} in the control, which is 43.6–44.8% above sole maize and 5.2–5.6 times the sole-soybean value, and rose to 9.21–10.04 g m^{-2} d^{-1} under moderate fertilization. During grain filling, canopy NAR was 8.39–10.78 g m−2 d−1; when each intercrop was compared with sole maize at the same fertilization level, this corresponded to 71.9–118.2% higher NAR, and over the final interval it remained at 4.76–5.99 g m^{-2} d^{-1}, sufficient to support maturation of both components. The maize component itself gained 10.8–27.3% and the soybean component 10.9–26.1% relative to their respective sole crops, so the canopy advantage arose from a genuine increase in both components rather than from the addition of a second species alone.

Yield structure of maize

The 1000-kernel weight of sole maize was 343.0 g in the control, which is typical of the FAO 340 maturity group, and rose to 352.0 g under $N_{60}P_{45}K_{45}$ and 361.0 g under $N_{90}P_{60}K_{60}$, gains of 2.6% and 5.2% attributable to a longer grain-filling period and more intensive assimilate transport (Table 3). In the intercrops, the corresponding values were 340.0–341.0 g in the control and 359.0–359.5 g under intensive fertilization, so the reduction of 0.3–0.9% relative to sole cropping was well below $LSD_{0.05}$ = 12.9 g and was therefore not significant, indicating that kernel size was fully maintained under intercropping. Shelling percentage behaved similarly, at 83.1% for sole maize and 83.0–83.3% in the intercrops under the control, rising to 85.0% under $N_{90}P_{60}K_{60}$ in both

systems as kernel set improved and the proportion of cob core declined; none of the differences between sole and intercropped stands approached $LSD_{0.05}$ = 4.2%.

Table 3: Yield structure of maize in sole and binary stands (five-year means, 2021–2025)

Cultivar or hybrid	*Fertilisation*	*1000-kernel weight, g*	*Shelling percentage, %*	*Ear length, cm*	*Kernel rows per ear, no.*	*Kernels per row, no.*
RZhT Zanetikks (sole)	Control	343.0	83.1	22.0	16	34.0
	$N_{60}P_{45}K_{45}$	352.0	84.0	22.4	18	35.2
	$N_{90}P_{60}K_{60}$	361.0	85.0	22.9	18	36.6
Zanetikks + Sireliya (intercrop)	Control	341.0	83.0	22.0	16	33.8
	$N_{60}P_{45}K_{45}$	351.7	83.7	23.0	18	35.0
	$N_{90}P_{60}K_{60}$	359.5	85.0	23.4	18	36.2
Zanetikks + Sakuza (intercrop)	Control	340.0	83.3	21.7	16	34.1
	$N_{60}P_{45}K_{45}$	350.3	84.0	22.5	18	35.6
	$N_{90}P_{60}K_{60}$	359.0	84.9	23.0	18	36.5
$LSD_{0.05}$, individual means		12.9	4.2	1.1	1.0	2.3
$LSD_{0.05}$ for factor A		4.3	1.5	0.3	0.4	1.0
$LSD_{0.05}$ for factor B		4.2	1.5	0.4	0.4	0.8
$LSD_{0.05}$ for A × B		4.1	1.2	0.4	0.2	0.5

Four least significant differences are given for each trait. The first applies to comparisons among the individual treatment means shown in the body of the table; the remaining three apply, respectively, to comparisons among the marginal means of cropping system, among the marginal means of fertilization, and among the interaction means. Any difference exceeding the relevant $LSD_{0.05}$ is significant at p = 0.05.

Ear morphometrics responded to fertilization but changed little between cropping systems. Ear length was 22.0 cm in sole cropping and 21.7–22.0 cm in the intercrops under the control, and fertilization extended it to 22.9–23.4 cm, a gain of 4.1–6.4% that exceeds $LSD_{0.05}$ = 1.1 cm and reflects additional kernel set in the apical part of the ear. The number of kernel rows rose from 16 in the control to 18 under both fertilized regimes in every cropping system, a change of exactly $LSD_{0.05}$ = 1.0 and therefore at the limit of significance, which is consistent with the strong genetic determination and low phenotypic plasticity of this trait. Kernels per row increased from 33.8–34.0 in the control to 36.2–36.6 under $N_{90}P_{60}K_{60}$, a gain of 6.5–7.6% that exceeds $LSD_{0.05}$ = 2.3 and is attributable to improved pollination and reduced ovary abortion. Comparison of the two cropping systems showed a tendency towards slightly longer ears in the intercrops (+0.4–0.5 cm) accompanied by 0.2–0.4 fewer kernels per row, but neither difference reached $LSD_{0.05}$, so the apparent compensatory adjustment of ear structure under interspecific competition should be regarded as a trend rather than an established effect.

Yield structure of soybean

The two cultivars differed markedly in seed size, with Sireliya producing 206.0–215.8 g and Sakuza 187.1–200.0 g per 1000 seeds, a difference of 7.9–10.1% that greatly exceeds $LSD_{0.05}$ = 7.3 g and reflects their different genetic background and intended use

(Table 4). In the intercrops, the 1000-seed weight fell by 3.4–5.5% in Sireliya and by 3.1–5.1% in Sakuza, differences that are at or slightly above the LSD and are consistent with partial shading during seed filling and with competition for assimilates. The response to fertilization was weak in both cultivars, at 2.4–6.9% under $N_{60}P_{45}K_{45}$ and 4.8–7.0% under $N_{90}P_{60}K_{60}$, again reflecting symbiotic coverage of a large part of the nitrogen requirement.

Table 4: Yield structure of soybean in sole and binary stands (five-year means, 2021–2025)

Cultivar	*Fertilisation*	*1000-seed weight, g*	*Pods per plant, no.*	*Seeds per pod, no.*	*Seeds per plant, no.*	*Seed mass per plant, g*
Sireliya (sole)	Control	206.0	14.0	1.9	26.6	5.5
	$N_{60}P_{45}K_{45}$	211.0	16.0	2.4	38.6	8.1
	$N_{90}P_{60}K_{60}$	215.8	17.9	1.8	31.6	6.8
Sakuza (sole)	Control	187.1	16.3	2.0	33.4	6.2
	$N_{60}P_{45}K_{45}$	192.3	17.8	2.5	44.7	8.6
	$N_{90}P_{60}K_{60}$	200.0	21.0	1.5	32.0	6.4
Sireliya (intercrop with maize)	Control	199.0	18.9	2.5	47.3	9.4
	$N_{60}P_{45}K_{45}$	203.1	20.2	3.3	65.8	13.4
	$N_{90}P_{60}K_{60}$	204.0	21.3	2.7	57.8	11.8
Sakuza (intercrop with maize)	Control	181.2	20.4	2.7	55.5	10.1
	$N_{60}P_{45}K_{45}$	187.0	21.5	3.5	75.1	14.0
	$N_{90}P_{60}K_{60}$	189.8	23.0	2.9	67.2	12.8
$LSD_{0.05}$, individual means		7.3	1.1	0.4	2.5	0.2
$LSD_{0.05}$ for factor A		4.3	1.5	0.3	0.4	1.0
$LSD_{0.05}$ for factor B		4.2	1.5	0.4	0.4	0.8
$LSD_{0.05}$ for A × B		4.1	1.2	0.4	0.2	0.5

Values are per plant. Four least significant differences are given for each trait, applying respectively to individual treatment means, to the marginal means of cropping system, to the marginal means of fertilization and to the interaction means.

Pods per plant increased from 14.0–16.3 in sole cropping under the control to 17.9–21.0 under fertilization, and in the intercrops reached 18.9–23.0, an increase of 35.0–40.0% over sole cropping that far exceeds $LSD_{0.05}$ = 1.1 and represents an unambiguous compensatory response to halved density. Seeds per pod followed a more complex pattern. In sole cropping, the trait rose from 1.9–2.0 in the control to 2.4–2.5 under $N_{60}P_{45}K_{45}$ but fell to 1.5–1.8 under $N_{90}P_{60}K_{60}$, a depression of pod seed set consistent with disturbance of hormonal balance at high nitrogen supply. In the intercrops it was uniformly higher, at 2.5–2.7 in the control and 2.7–3.5 under fertilization, with a maximum of 3.5 seeds per pod in Sakuza under $N_{60}P_{45}K_{45}$, that is 40.0% above the corresponding sole crop. Because these differences exceed $LSD_{0.05}$ = 0.4, the advantage of the intercrop for this trait is statistically supported.

Seeds per plant, which integrates the preceding components, was 26.6–33.4 in sole cropping under the control and reached 38.6–44.7 under $N_{60}P_{45}K_{45}$, whereas in the

intercrops it attained 47.3–55.5 in the control and 65.8–75.1 under moderate fertilization, corresponding to increases of 66.2–77.8% and 68.0–70.5% respectively. Seed mass per plant, the most direct agronomic expression of individual plant productivity, rose from 5.5–6.2 g in sole cropping under the control and 8.1–8.6 g under $N_{60}P_{45}K_{45}$ to 9.4–10.1 g and 13.4–14.0 g in the intercrops, gains of 62.9–70.9% and 62.8–65.4%. All of these differences exceed the respective $LSD_{0.05}$ values by a wide margin.

Correlations among yield components

For maize, 1000-kernel weight was strongly and positively associated with shelling percentage ($r = 0.78$, $p < 0.01$), which indicates synchronous development of the two traits, and ear length correlated closely with kernels per row ($r = 0.82$, $p < 0.01$) but only weakly with the number of kernel rows ($r = 0.35$, $p > 0.05$). The strongest associations with grain yield were those of kernels per ear ($r = 0.89$, $p < 0.001$) and 1000-kernel weight ($r = 0.75$, $p < 0.01$), whereas shelling percentage was only moderately associated ($r = 0.52$, $p < 0.05$), confirming its secondary role in yield determination. For soybean, pod number and seeds per pod were negatively associated ($r = -0.42$, $p < 0.05$), which is the expected signature of competition for assimilates among reproductive sites, and 1000-seed weight was only weakly related to the remaining components ($r = 0.18$–0.35, $p > 0.05$), consistent with strong genetic control. Seeds per plant ($r = 0.92$, $p < 0.001$) and seed mass per plant ($r = 0.95$, $p < 0.001$) showed the closest associations with seed yield, which underlines the importance of stand density management in realizing the yield potential of the crop.

Grain yield

Sole maize responded strongly to intensification. The five-year mean yield in the unfertilized control was 7.28 ± 0.54 t ha^{-1}, ranging from 5.45 t ha^{-1} in the unfavorable season of 2022 to 8.70 t ha^{-1} in the favorable season of 2023 (Table 5). Moderate fertilization raised the mean to 9.39 ± 0.57 t ha^{-1}, a gain of 29.0%, and the response was largest in the drought season of 2022 (+35.0%), which points to a role of adequate mineral nutrition in maintaining performance under water limitation. The intensive regime raised the mean further to 10.45 ± 0.62 t ha^{-1}, or 43.5% above the control, with a maximum of 11.91 t ha^{-1} in 2023, but the marginal gain from $N_{60}P_{45}K_{45}$ to $N_{90}P_{60}K_{60}$ was only 11.3%, indicating that the response was approaching a plateau.

Sole soybean produced lower absolute yields and showed a distinctly non-monotonic response to fertilization. Cultivar Sireliya yielded 2.26 ± 0.10 t ha^{-1} in the control, rising to a maximum of 3.33 ± 0.19 t ha^{-1} under $N_{60}P_{45}K_{45}$ (+47.3%) but falling to 2.80 ± 0.12 t ha^{-1} under $N_{90}P_{60}K_{60}$. Cultivar Sakuza had a higher baseline of 2.55 ± 0.12 t ha^{-1} and followed the same pattern, with a maximum of 3.52 ± 0.18 t ha^{-1} under moderate fertilization and a decline to 2.63 ± 0.13 t ha^{-1} under the intensive regime, a reduction of 25.3% relative to $N_{60}P_{45}K_{45}$ that greatly exceeds the applicable $LSD_{0.05}$.

Doi: https://doi.org/10.33002/nr2581.6853.090206 Open Access

Table 5: Grain yield of maize and soybean in sole and binary stands, t ha^{-1} (2021–2025)

Cultivar or hybrid	*Fertilisation*	*2021*	*2022*	*2023*	*2024*	*2025*	*Mean ± SE*
RZhT Zanetikks (sole)	Control	7.85	5.45	8.70	7.48	6.93	7.28 ± 0.54
	$N_{60}P_{45}K_{45}$	10.01	7.36	10.62	9.97	8.99	9.39 ± 0.57
	$N_{90}P_{60}K_{60}$	11.44	8.35	11.91	10.52	10.03	10.45 ± 0.62
Sireliya (sole)	Control	2.32	1.90	2.51	2.30	2.25	2.26 ± 0.10
	$N_{60}P_{45}K_{45}$	3.56	2.73	3.79	3.44	3.11	3.33 ± 0.19
	$N_{90}P_{60}K_{60}$	2.89	2.37	3.11	2.87	2.77	2.80 ± 0.12
Sakuza (sole)	Control	2.59	2.15	2.89	2.62	2.50	2.55 ± 0.12
	$N_{60}P_{45}K_{45}$	3.67	2.84	3.92	3.63	3.54	3.52 ± 0.18
	$N_{90}P_{60}K_{60}$	2.69	2.19	2.93	2.79	2.52	2.63 ± 0.13
Zanetikks + Sireliya, maize component	Control	8.45	6.10	9.49	8.25	8.30	8.12 ± 0.55
	$N_{60}P_{45}K_{45}$	11.60	8.39	12.79	11.03	10.39	10.84 ± 0.73
	$N_{90}P_{60}K_{60}$	13.39	10.06	14.23	12.28	11.68	12.33 ± 0.72
Zanetikks + Sireliya, soybean component	Control	1.92	1.58	2.03	1.80	1.81	1.83 ± 0.08
	$N_{60}P_{45}K_{45}$	2.70	2.21	2.84	2.72	2.57	2.61 ± 0.11
	$N_{90}P_{60}K_{60}$	2.35	2.02	2.60	2.35	2.29	2.32 ± 0.09
Zanetikks + Sireliya, system total	Control	10.40	7.91	11.18	10.20	9.91	9.92 ± 0.55
	$N_{60}P_{45}K_{45}$	14.40	10.80	15.60	13.60	13.68	13.61 ± 0.79
	$N_{90}P_{60}K_{60}$	16.36	11.39	17.01	15.14	13.14	14.61 ± 1.04
Zanetikks + Sakuza, maize component	Control	8.63	6.76	9.34	7.95	8.37	8.21 ± 0.43
	$N_{60}P_{45}K_{45}$	12.09	9.03	12.70	11.03	10.49	11.07 ± 0.64
	$N_{90}P_{60}K_{60}$	13.08	9.86	13.72	13.16	12.42	12.45 ± 0.68
Zanetikks + Sakuza, soybean component	Control	2.03	1.65	2.20	1.99	1.91	1.96 ± 0.09
	$N_{60}P_{45}K_{45}$	2.84	2.29	3.08	2.81	2.68	2.74 ± 0.13
	$N_{90}P_{60}K_{60}$	2.56	2.21	2.71	2.47	2.57	2.51 ± 0.08
Zanetikks + Sakuza, system total	Control	10.78	7.95	11.52	10.44	9.84	10.11 ± 0.60
	$N_{60}P_{45}K_{45}$	14.25	11.09	15.51	14.35	13.18	13.68 ± 0.74
	$N_{90}P_{60}K_{60}$	16.29	11.43	16.90	15.78	15.27	15.13 ± 0.97
$LSD_{0.05}$, individual means		0.12	0.14	0.18	0.11	0.13	0.10
$LSD_{0.05}$ for factor A		0.05	0.06	0.05	0.06	0.04	0.03
$LSD_{0.05}$ for factor B		0.05	0.05	0.08	0.03	0.05	0.04
$LSD_{0.05}$ for A × B		0.02	0.03	0.05	0.02	0.04	0.03

Note: SE is the standard error of the five-year mean and therefore expresses interannual rather than within-season variation. The first $LSD_{0.05}$ row applies to comparisons among the individual treatment means within a season; the following three rows give the least significant differences for the marginal means of cropping system, for the marginal means of fertilization and for the interaction, respectively.

The maize component of the intercrops out-yielded sole maize at every fertilization level despite identical maize plant density. In combination with Sireliya, it reached 8.12 ± 0.55 t ha^{-1} in the control (+11.5%), 10.84 ± 0.73 t ha^{-1} under $N_{60}P_{45}K_{45}$ (+15.4%) and 12.33 ± 0.72 t ha^{-1} under $N_{90}P_{60}K_{60}$ (+18.0%), with a seasonal maximum of 14.23 t ha^{-1} in 2023. In combination with Sakuza, the corresponding values were 8.21 ± 0.43 t ha^{-1} (+12.7%), 11.07 ± 0.64 t ha^{-1} (+17.9%) and 12.45 ± 0.68 t ha^{-1} (+19.1%). All of these differences exceed the seasonal $LSD_{0.05}$ values of 0.11–0.18 t ha^{-1} and were reproduced in each of the five seasons, so the effect is both statistically significant and temporally consistent. The soybean component yielded less than sole soybean per unit ground area, at 1.83–1.96 t ha^{-1} in the control (78.4–82.9% of sole cropping across the three fertilization levels), which is nevertheless well above the 50% that would be expected

from the halved seeding rate alone, and per-plant productivity in the intercrop was correspondingly some 54–62% higher than in sole cropping.

Summed over both components, the intercrop with Sireliya produced 9.92 ± 0.55 t ha^{-1} in the control, 13.61 ± 0.79 t ha^{-1} under $N_{60}P_{45}K_{45}$ and 14.61 ± 1.04 t ha^{-1} under $N_{90}P_{60}K_{60}$, exceeding sole maize under the same regime by 36.3%, 44.9% and 39.8% respectively. The intercrop with Sakuza produced 10.11 ± 0.60, 13.68 ± 0.74 and 15.13 ± 0.97 t ha^{-1}, or 38.9%, 45.7% and 44.8% above sole maize, with the highest single-season total of 17.01 t ha^{-1} recorded in 2023.

Land-use efficiency, agronomic efficiency and yield stability

Season effects were pronounced across all treatments. The 2022 season was the most unfavorable, with yields 18–31% below the five-year mean in all treatments, whereas 2023 delivered yields 15–22% above the mean. Against this background, the three efficiency and stability measures given in Table 6 characterize the systems in complementary ways.

Table 6: Land equivalent ratio, agronomic efficiency and interannual stability of the cropping systems (2021–2025)

System	*Fertilisation*	*LER_{maize}*	*$LER_{soybean}$*	*LER total*	*AE, kg grain per kg N*	*CV, %*	*S_i*	*b_i*
Sole maize	Control	—	—	1.00	—	16.6	0.626	1.37
	$N_{60}P_{45}K_{45}$	—	—	1.00	35.2	13.6	0.693	1.11
	$N_{90}P_{60}K_{60}$	—	—	1.00	35.2	13.3	0.701	1.09
Sole soybean Sireliya	Control	—	—	1.00	—	9.8	0.757	0.81
	$N_{60}P_{45}K_{45}$	—	—	1.00	17.8	12.4	0.720	1.01
	$N_{90}P_{60}K_{60}$	—	—	1.00	6.0	9.7	0.762	0.80
Sole soybean Sakuza	Control	—	—	1.00	—	10.5	0.744	0.85
	$N_{60}P_{45}K_{45}$	—	—	1.00	16.2	11.5	0.724	0.94
	$N_{90}P_{60}K_{60}$	—	—	1.00	0.9	10.9	0.747	0.87
Zanetikks + Sireliya	Control	1.115	0.810	1.93	—	14.1	0.667	1.15
	$N_{60}P_{45}K_{45}$	1.154	0.784	1.94	61.5	13.9	0.678	1.15
	$N_{90}P_{60}K_{60}$	1.180	0.829	2.01	52.1	12.3	0.718	1.00
Zanetikks + Sakuza	Control	1.127	0.767	1.89	—	11.3	0.729	0.91
	$N_{60}P_{45}K_{45}$	1.179	0.778	1.96	59.5	12.4	0.717	1.01
	$N_{90}P_{60}K_{60}$	1.191	0.954	2.15	55.8	11.3	0.735	0.92

Note: LER components were computed from the five-year mean yields of Table 5 as defined in Section 2.5. AE is expressed per kg of applied nitrogen and refers to the total system yield. CV, S_i and b_i characterize the five annual system yields; b_i was computed on the dimensionless relative scale described in Section 2.5.

Partial LER for maize exceeded unity in every intercrop and at every fertilization level, ranging from 1.115 to 1.191 and increasing with nitrogen supply. Partial LER for soybean ranged from 0.767 to 0.954 and thus consistently exceeded the value of 0.50

that the halved seeding rate alone would predict. Total LER ranged from 1.89 in the unfertilized Sakuza combination to 2.15 in the same combination under $N_{90}P_{60}K_{60}$, and computed season by season, the estimates were highly repeatable, at 1.90 ± 0.02 to 2.15 ± 0.03 depending on treatment.

Agronomic efficiency differed sharply between systems. For sole maize it was 35.2 kg grain per kg N at both fertilization levels, so the crop continued to convert additional nitrogen into grain at an undiminished marginal rate over the range tested. For sole soybean it fell from 16.2–17.8 kg kg^{-1} at $N_{60}P_{45}K_{45}$ to 0.9–6.0 kg kg^{-1} at $N_{90}P_{60}K_{60}$, reflecting the yield depression at the higher rate. The intercrops achieved 59.5–61.5 kg grain per kg N at $N_{60}P_{45}K_{45}$, which is 69–75% above sole maize, and this fell to 52.1–55.8 kg kg^{-1} at $N_{90}P_{60}K_{60}$, so within the range examined the moderate regime was the more efficient one for the intercrop even though it was not the highest-yielding (Figure 5).

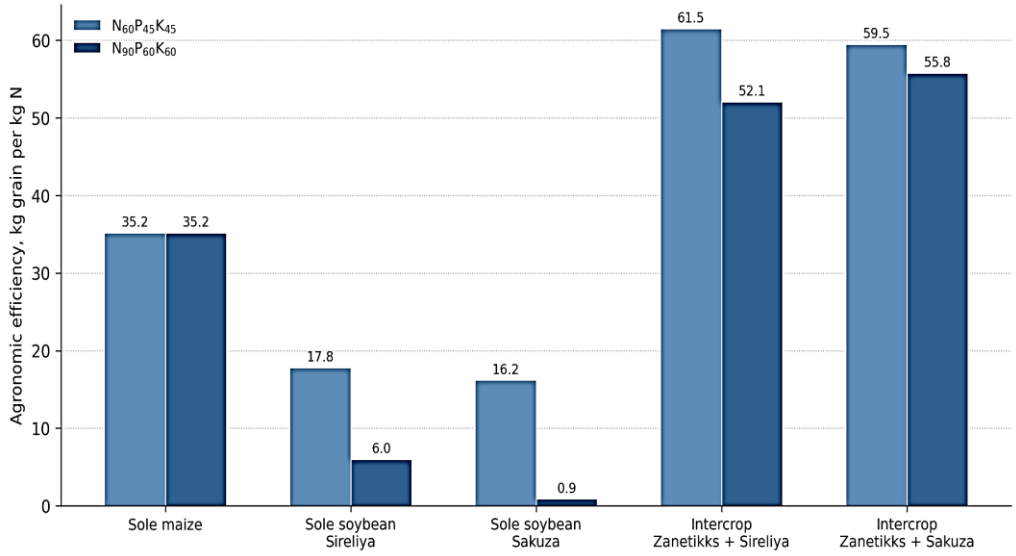

Figure 5: Agronomic efficiency of applied nitrogen in sole and intercropped stands, expressed as kg of grain per kg of applied N (means for 2021–2025).

Interannual variability was lowest in sole soybean (CV = 9.7–12.4%), highest in sole maize under the control (CV = 16.6%), and intermediate in the intercrops (CV = 11.3–14.1%), and in both maize-containing systems, fertilization reduced CV. The yield stability index ranked the systems in the same order, at 0.626–0.701 for sole maize, 0.720–0.762 for sole soybean and 0.667–0.735 for the intercrops. Regression on the environmental index gave b_i = 1.09–1.37 for sole maize, indicating a system that gains disproportionately in favorable seasons and loses disproportionately in poor ones, b_i = 0.80–1.01 for sole soybean, indicating a conservative response, and b_i = 0.91–1.15 for the intercrops, which is close to unity and denotes broad adaptability. Deviations from regression were small in all cases, so the fitted responses describe the systems adequately.

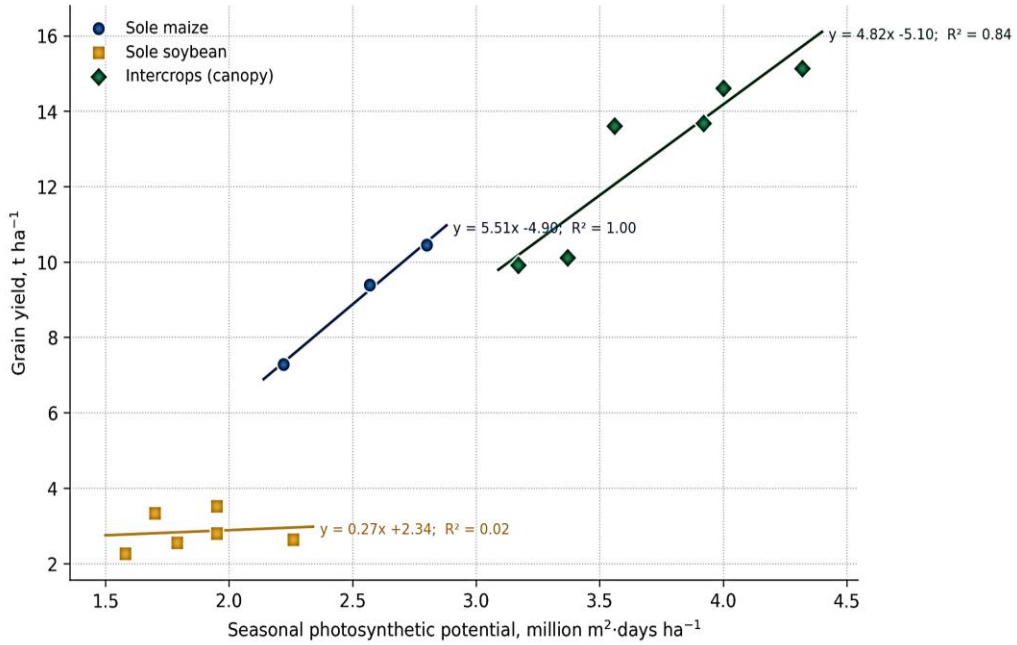

Figure 6: Grain yield in relation to seasonal photosynthetic potential across all fifteen treatment combinations (means for 2021–2025). Fitted linear regressions are shown for each group of systems.

Plotting yield against seasonal PP across all fifteen treatment combinations revealed that the two groups behaved in fundamentally different ways (Figure 6). For maize-containing systems, the relationship was close and positive, with $R^2 = 1.00$ for sole maize and $R^2 = 0.84$ for the intercrops, and the two regression lines had similar slopes of 5.51 and 4.82 t ha^{-1} per million m^2·days ha^{-1}. For sole soybean, the relationship effectively disappeared ($R^2 = 0.02$), because the highest fertilization regime enlarged the assimilatory surface while simultaneously depressing seed set, so that additional PP was not converted into additional yield. Photosynthetic potential is therefore a reliable predictor of productivity only where sink capacity expands in step with source capacity.

Because only three fixed fertilizer regimes were compared, the data were not used to extrapolate an intermediate fertilizer optimum. Agronomic and economic recommendations are therefore restricted to the fertilizer rates actually tested.

Indicative partial budget

Because the systems differ in the value as well as the quantity of the harvest, gross margins were computed on a partial-budget basis (Table 7). Sole maize returned 62,176 UAH ha^{-1} in the unfertilized control and 76,033 UAH ha^{-1} under the intensive regime. Sole soybean returned less at every fertilization level and lost value under $N_{90}P_{60}K_{60}$, where yield depression outweighed the additional input cost. The intercrops returned 101,306–104,656 UAH ha^{-1} in the control and 134,237–139,027 UAH ha^{-1} under intensive fertilization, exceeding sole maize under the same regime by 63–68% in the control, by 85–91% under $N_{60}P_{45}K_{45}$ and by 77–83% under $N_{90}P_{60}K_{60}$.

Table 7: Indicative partial budget of the cropping systems, UAH ha^{-1} (five-year mean yields, prices of mid-2026)

System	*Fertilisation*	*Revenue*	*Variable cost*	*Gross margin*	*Difference from sole maize*
Sole maize	Control	66,976	4,800	62,176	—
	$N_{60}P_{45}K_{45}$	86,388	15,604	70,784	—
	$N_{90}P_{60}K_{60}$	96,140	20,107	76,033	—
Sole soybean Sireliya	Control	43,844	3,900	39,944	−22,232
	$N_{60}P_{45}K_{45}$	64,602	14,704	49,898	−20,886
	$N_{90}P_{60}K_{60}$	54,320	19,207	35,113	−40,920
Sole soybean Sakuza	Control	49,470	3,900	45,570	−16,606
	$N_{60}P_{45}K_{45}$	68,288	14,704	53,584	−17,200
	$N_{90}P_{60}K_{60}$	51,022	19,207	31,815	−44,218
Zanetikks + Sireliya	Control	110,206	8,900	101,306	+39,130
	$N_{60}P_{45}K_{45}$	150,362	19,704	130,658	+59,874
	$N_{90}P_{60}K_{60}$	158,444	24,207	134,237	+58,204
Zanetikks + Sakuza	Control	113,556	8,900	104,656	+42,480
	$N_{60}P_{45}K_{45}$	155,000	19,704	135,296	+64,512
	$N_{90}P_{60}K_{60}$	163,234	24,207	139,027	+62,994

Note: Only variable costs that differ among the systems are included, as set out in Section 2.5. At the exchange rate prevailing in mid-2026, the intercrop gross margins correspond to approximately 2,400–3,300 USD ha^{-1} and those of sole maize to approximately 1,480–1,810 USD ha^{-1}.

Marginal analysis of raising fertilization from $N_{60}P_{45}K_{45}$ to $N_{90}P_{60}K_{60}$ gave contrasting results across the systems. The additional variable cost was 4,503 UAH ha^{-1} in every case. Sole maize generated 9,752 UAH ha^{-1} of additional revenue, giving a VCR of 2.17; after the added variable cost, gross margin increased by 5,249 UAH ha^{-1}. The intercrops generated 8,082–8,234 UAH ha^{-1} of additional revenue, corresponding to VCR values of 1.79–1.83; the associated increases in gross margin were 3,579–3,731 UAH ha^{-1}. Sole soybean generated negative additional revenue (−10,282 to −17,266 UAH ha^{-1}), and gross margin fell by 14,785–21,769 UAH ha^{-1}, so the intensive regime destroyed value in that system.

Sensitivity analysis showed that these two conclusions differ in their robustness. The advantage of the intercrop over sole maize was insensitive to the soybean-to-maize price ratio, remaining between 49,000 and 72,000 UAH ha^{-1} as the ratio varied from 1.5 to 2.4, so it does not depend on soybean commanding an unusual premium. The ranking of the two fertilization regimes, by contrast, was finely balanced. The intensive regime remained marginally the more profitable at current input prices, but the moderate regime overtook it once fertilizer prices rose by approximately 83% relative to grain prices, that is, at about 57 UAH kg^{-1} for ammonium nitrate and 60 UAH kg^{-1} for complex NPK.

Discussion

What changed in the canopy, and what did not

The central physiological result of this experiment is that the intercrop advantage was built almost entirely from canopy size and canopy duration rather than from a transformation of leaf-level performance. The two components together maintained a canopy LAI well above the optimum normally reported for sole stands, and the additional leaf area was retained long enough to lift seasonal PP by roughly half over sole maize. Critically, the added leaf area did not behave as redundant self-shading tissue. Efficiency of PP conversion into grain rose rather than fell, and the yield–LAI correlation tightened relative to sole cropping, which is the expected signature of vertical stratification in a C_4–C_3 mixture where the tall component intercepts direct radiation and the short component operate on transmitted and diffuse light (Brooker *et al.*, 2015; Gou *et al.*, 2016).

Chen *et al.* (2025) reached a closely analogous conclusion in a semi-arid Chinese system, finding that intercropping raised biomass and grain yield by enlarging leaf area index rather than by improving leaf photosynthetic parameters. The present data extend that finding to a rainfed temperate chernozem and add a temporal dimension, because the two species occupied different critical windows. Maize yield tracked PP accumulated between the 15-leaf stage and silking, whereas soybean yield tracked PP accumulated from the milk stage onward, and it is this offset that allows the canopy to remain photosynthetically active across a longer fraction of the season than either component alone. Canopy NAR nevertheless rose in both components, not only in the mixture as a whole, which indicates that the intercrop also improved the light environment experienced by individual leaves and not merely the amount of leaf surface exposed to it.

Quantifying the yield advantage, and the limits of that quantification

Maize yielded 11.5–19.1% more in the intercrop than in sole cropping at identical plant density and identical fertilizer rate per unit of total area. Because the density of the maize component was held constant, this increment cannot be explained by a change in maize population and constitutes overyielding in the strict sense (Li *et al.*, 2014). The corresponding partial LER for maize, consistently between 1.12 and 1.19, provides a formal index of this facilitation that is independent of the design used for the companion crop, and it is this index rather than the total LER that should be read as the quantitative measure of interspecific benefit in the present study. The magnitude is modest relative to the 30–34% maize yield gain reported by Nasar *et al.* (2023) under a much higher nitrogen supply, but it was reproduced in five consecutive seasons of contrasting weather, which strengthens confidence in the effect.

The total LER of 1.89–2.15 requires careful framing and should not be compared directly with meta-analytic means. The present experiment used an additive design in which soybean was added to a full maize stand rather than substituted for part of it, so total plant population exceeded that of either sole crop and total LER is inflated relative to the values obtained in replacement designs. Global syntheses of maize–soybean intercropping report mean LER close to 1.3 (Xu *et al.*, 2020), and broader analyses of annual intercrops report

about 1.2 (Yu *et al.*, 2015), but these summarize a literature dominated by substitutive and relay arrangements. Studies that likewise increased total density report values in the range observed here, with Du *et al.* (2018) documenting LER as high as 2.2 in optimized maize–soybean strip systems. The interpretation supported by the present data is therefore that the system converts land into grain far more effectively than sole maize, while the extent to which that gain reflects facilitation as opposed to fuller occupation of the available niche must be read from the partial LER of maize.

The soybean component reached 77–83% of sole-crop yield per unit ground area from half the seeding rate, which corresponds to a 54–62% increase in individual plant productivity delivered mainly through additional pods and seeds per pod. Comparable plasticity has been documented for soybean in double-row intercrops under drought (Kisman *et al.*, 2025), and it is this compensatory capacity, rather than any change in maize performance alone, that makes the additive arrangement viable.

Nitrogen dynamics as a plausible rather than a demonstrated mechanism

The facilitative pattern observed here is consistent with improved nitrogen nutrition of maize, but the present experiment did not measure nodulation, symbiotic nitrogen fixation, isotopic tracers, rhizodeposition or soil mineral nitrogen dynamics, and no direct evidence of nitrogen transfer was obtained. The nitrogen interpretation is therefore advanced as a plausible mechanism to be tested rather than as a demonstrated cause, and two distinct routes remain unresolved. Nitrogen may reach maize directly, through rhizodeposition, nodule turnover and mycorrhizal networks, for which the reviewed evidence suggests a transfer of the order of 10–15% of fixed nitrogen to a companion cereal (Peoples *et al.*, 2009; Thilakarathna *et al.*, 2016). Alternatively, the benefit may be indirect, arising because the legume covers much of its own nitrogen demand symbiotically and thereby competes less strongly for soil mineral nitrogen, leaving a larger share to maize. Facilitation may also operate through phosphorus and micronutrient mobilization rather than nitrogen at all (Li *et al.*, 2014). Distinguishing these routes requires ^{15}N labelling together with nodulation assessment, and this is the most important extension of the present work.

The behavior of soybean under high fertilization is at least indirectly informative. Sole soybean lost 16–25% of its yield when nitrogen rose from 60 to 90 kg ha^{-1}, which matches the well-documented suppression of symbiotic fixation by mineral nitrogen (Crews and Peoples, 2004; Salvagiotti *et al.*, 2008), whereas the intercropped soybean lost only 9–12%. A parsimonious reading is that competition from maize lowered mineral nitrogen availability in the soybean rhizosphere and so partially protected the symbiosis, but this remains an inference from yield behavior rather than a measured effect.

For the same reason, the term synergy is used in this paper only where a quantitative index supports it. The maize partial LER above unity and the increase in NAR of both components relative to their sole crops qualify on that basis; the descriptive impression of mutual stimulation elsewhere in the dataset does not, and has been framed accordingly.

Fertilization strategy

The intercrops converted applied nitrogen into grain far more efficiently than sole maize, at roughly 60 kg grain per kg N under the moderate regime against 35 kg kg^{-1} for sole maize, and this efficiency declined at the higher rate while sole maize maintained its marginal response. Two considerations therefore point towards a moderate regime for the intercrop. First, agronomic efficiency was maximized there. Second, the higher rate depressed the soybean component and eroded the protein contribution that is the distinctive product of the system. This is consistent with the meta-analytic finding of Xu *et al.* (2020) that increasing nitrogen input scarcely changes LER while significantly reducing intercropped soybean yield, and with the conclusion of Du *et al.* (2018) that optimized maize–soybean systems can balance productivity against sustainability.

Two further consequences of the moderate regime deserve mention. The intercrop delivers protein and starch from the same field in a ratio close to that required for balanced ruminant and monogastric rations, which is directly relevant to integrated crop–livestock systems and reduces dependence on imported protein feed (Lemaire *et al.*, 2014). In addition, the larger and more diverse belowground input of an intercrop has been shown to raise soil carbon and nitrogen stocks relative to sole cropping (Cong *et al.*, 2015), which matters on chernozem where humus decline under intensive arable use is a documented concern for the zone (Prysiazhniuk *et al.*, 2025). Neither soil carbon nor grain composition was quantified in the present experiment, so both are noted as expected co-benefits rather than as results.

The highest total yield in this experiment was, however, obtained under $N_{90}P_{60}K_{60}$ rather than under the moderate regime, and the indicative partial budget of Section 3.9 does not overturn this. At mid-2026 Ukrainian prices, the intensive regime remained marginally the more profitable choice for the intercrop, by some 3,600–3,700 UAH ha^{-1}. What the budget does show is that the margin of advantage is thin and that the VCR for the additional fertilizer (1.79–1.83) falls below the value of about 2.0 conventionally taken as the threshold at which a producer should accept the additional cash outlay and risk. The moderate regime becomes the more profitable option once fertilizer prices rise by roughly 83% relative to grain, a shift well within the range experienced by Ukrainian producers in recent seasons. The case for the observed $N_{60}P_{45}K_{45}$ regime rests on three arguments taken together, namely a VCR below the adoption threshold, the substantially higher efficiency of nitrogen use, and the protection of the soybean component that gives the system its distinctive protein output. It does not rest on profit maximization at any single set of prices, and it remains to be validated across more than one site. Published assessments from other environments likewise report higher net returns for maize–soybean intercropping than for sole maize (Raza *et al.*, 2022), but the absolute figures are not transferable, and the present budget should be read as indicative rather than definitive.

Stability, and how far these results travel

The intercrops combined the highest absolute productivity in the experiment with an interannual variability lower than that of sole maize and a regression coefficient close to unity, which denotes a system that responds proportionally to the environment rather

than one that gains disproportionately in good seasons and collapses in poor ones. The advantage was clearest in the drought season of 2022. Meta-analytic evidence indicates that cereal–legume intercrops generally buffer yield variability relative to sole cereals (Martin-Guay *et al.*, 2018; Raseduzzaman and Jensen, 2017), and the present five-year dataset is consistent with that generalization on chernozem.

Three qualifications bound the transferability of these findings. The first concerns environment. The results were obtained on a fertile rainfed chernozem in a moderately continental climate, and the same canopy logic should apply across temperate systems with comparable radiation and season length, including much of Central and Eastern Europe, but the absolute yield levels depend on the high baseline fertility of the soil and would not be reproduced on lighter or shallower profiles. Under drier or more strongly water-limited conditions, the additive arrangement, which raises total transpiring leaf area, may become a liability rather than an asset, and a substitutive arrangement would then be the safer design. The second concerns mechanization. The 70 cm maize row spacing with a single interposed soybean row is compatible with existing row-crop equipment for sowing and inter-row operations, yet harvest requires two passes at different maturity dates and the arrangement offers no scope for the wide-strip layouts developed specifically for machine harvest in China (Du *et al.*, 2018). The system is therefore well matched to smallholder and mid-scale operations and to mixed crop–livestock farms that value on-farm protein, whereas large mechanized enterprises would need either strip widths adapted to header geometry or components with synchronized maturity. The third concerns climate change. If the projected increase in drought frequency in the Forest-Steppe (Prysiazhniuk *et al.*, 2023; Shvidenko *et al.*, 2017) is realized, the buffering observed in 2022 becomes more valuable, but the very canopy expansion that generates the yield advantage also raises seasonal water demand, and the water balance of the system was not measured here. Coupling this design to explicit water-use measurement, as done by Raza *et al.* (2022) in semi-arid conditions, is a necessary next step before the system is recommended as a climate-adaptation measure.

Limitations

Four limitations should be borne in mind. Nitrogen fixation and transfer were inferred rather than measured. The economic assessment is a partial budget resting on a single set of prices and on the assumption that cost items common to all treatments are equal; it omits labour, machinery depreciation and the risk premium attaching to a less familiar system, and a full enterprise budget built on multi-year price series would be needed before the fertilization ranking could be regarded as settled. The experiment was conducted at a single site, so genotype-by-environment interaction across the wider Forest-Steppe remains untested. Finally, the additive design means that total LER overstates the land-sparing benefit relative to a substitutive comparison, and the partial LER of maize should be preferred as the measure of facilitation.

Conclusions

Binary maize–soybean intercropping on typical chernozem of the Ukrainian Forest-Steppe reorganizes the photosynthetic apparatus in a way that is quantitatively different from either sole crop, and the reorganization is one of canopy architecture rather than of

leaf-level physiology. The two components together sustained a canopy LAI of 6.56–6.81 and a seasonal photosynthetic potential of 4.00–4.32 million $m^2 \cdot$days ha^{-1}, roughly half again as much as sole maize, and because the two species occupied offset critical periods the canopy remained productive across a longer fraction of the season. That this additional leaf area was functional rather than redundant is shown by the simultaneous rise in photosynthetic potential use efficiency and net assimilation rate.

The physiological gain translated into a system yield of 9.92–15.13 t ha^{-1}, exceeding sole maize by 36–45%, and into a maize component yield 11.5–19.1% above sole cropping at unchanged maize density. The latter is the key result, because it is independent of the design used for the companion crop and is expressed formally in a partial land equivalent ratio for maize of 1.12–1.19. Soybean contributed 1.83–2.74 t ha^{-1} of protein-rich grain from half its normal seeding rate through a compensatory increase in individual plant productivity. Total land equivalent ratio reached 1.89–2.15, a figure that reflects both facilitation and the additive design and should be interpreted with that qualification.

The intercrop converted applied nitrogen into grain at roughly 60 kg per kg N under $N_{60}P_{45}K_{45}$ against 35 kg per kg N for sole maize, and this efficiency declined at the higher rate while the soybean component was depressed. An indicative partial budget placed the gross margin of the intercrop at 101,000–139,000 UAH ha^{-1} against 62,000–76,000 UAH ha^{-1} for sole maize, an advantage of 63–91% that proved insensitive to the soybean-to-maize price ratio. Within the intercrop, the intensive regime remained marginally the more profitable at present prices, but with a value-cost ratio (VCR) of only 1.79–1.83, below the threshold conventionally required for adoption, and the moderate regime overtakes it if fertilizer prices rise by about 83% relative to grain. Among the tested rates, $N_{60}P_{45}K_{45}$ is therefore indicated for the region on the combined grounds of VCR, nitrogen-use efficiency and protection of the soybean component, with the explicit caveat that maximum total yield was obtained at the higher rate. The systems also proved broadly adapted, with a regression coefficient close to unity and interannual variability below that of sole maize, which is directly relevant where drought frequency is projected to rise.

Taken together, these findings position binary maize–soybean intercropping as a practical route to sustainable intensification on temperate chernozem, capable of producing energy feed and protein feed from the same field, of reducing nitrogen input per unit of output, of buffering weather-driven yield variability and of raising the gross margin per hectare well above that of sole maize. Realizing that potential at scale now depends on three things that lie beyond what this study could supply, namely direct measurement of nitrogen fixation and transfer, a full enterprise budget built on multi-year price series rather than the partial budget presented here, and multi-location validation across the Forest-Steppe.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*
Conceived and designed the research or analysis	Yes	No
Collected the data	Yes	No
Contributed to data analysis & interpretation	Yes	Yes
Wrote the article/paper	Yes	No
Critical revision of the article/paper	No	Yes
Editing of the article/paper	Yes	No
Supervision	No	Yes
Project Administration	No	Yes
Funding Acquisition	No	No
Overall Contribution Proportion (%)	60	40

Funding
No financial support was received for the research and writing of this article.

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The author(s) has/have NOT complied with PRISMA standards to an extent.

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Author(s) has/have no competing financial, professional, or personal interests from other parties or in publishing this manuscript. There is no conflict of interest with the publisher or the editorial team or the reviewers.

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