Integrated farming with intercropping increases food production while reducing environmental footprint

Qiang Chai[a,1], Thomas Nemecek[b], Chang Liang[c], Cai Zhao[a], Aizhong Yu[a], Jeffrey A. Coulter[d], Yifan Wang[a], Falong Hu[a], Li Wang[a,1], Kadambot H. M. Siddique[e], and Yantai Gan[f,1,2]

[a]Gansu Provincial Key Laboratory of Aridland Crop Sciences, College of Agronomy, Gansu Agricultural University, Lanzhou, 730070, China; [b]Agroscope, Life Cycle Assessment Research Group, CH-8046 Zurich, Switzerland; [c]Pollutant Inventories and Reporting Division, Environment and Climate Change Canada, Gatineau, QC K1A 0H3, Canada; [d]Department of Agronomy and Plant Genetics, University of Minnesota, St. Paul, MN 55108; [e]The University of Western Australia Institute of Agriculture, The University of Western Australia, Perth, WA 6001, Australia; and [f]Agriculture and Agri-Food Canada, Swift Current Research and Development Centre, Swift Current, SK S9H 3X2, Canada

Edited by Charles Godfray, University of Oxford, Oxford, United Kingdom, and accepted by Editorial Board Member Ruth DeFries June 10, 2021 (received for review April 9, 2021)

Food security has been a significant issue for the livelihood of smallholder family farms in highly populated regions and countries. Industrialized farming in more developed countries has increased global food supply to meet the demand, but the excessive use of synthetic fertilizers and pesticides has negative environmental impacts. Finding sustainable ways to grow more food with a smaller environmental footprint is critical. We developed an integrated cropping system that incorporates four key components: 1) intensified cropping through relay planting or intercropping, 2) within-field strip rotation, 3) soil mulching with available means, such as crop straw, and 4) no-till or reduced tillage. Sixteen field experiments, conducted with a wide range of crop inputs over 12 consecutive years (2006 to 2017), showed that the integrated system with intercropping generates significant synergies—increasing annual crop yields by 15.6 to 49.9% and farm net returns by 39.2% and decreasing the environmental footprint by 17.3%—when compared with traditional monoculture cropping. We conclude that smallholder farmers can achieve the dual goals of growing more food and lowering the environmental footprint by adopting integrated farming systems.

intercropping | relay-planting | environmental sustainability | rhizosphere | food security

About 83% of the global agricultural population (~2.3 billion) rely on smallholder farms for their livelihood (1). In developing countries/regions, such as Africa and southeastern Asia, many farm families face significant challenges related to the continuous production of sufficient quality food from limited farmable land areas (2, 3), a lack of available resources for agriculture (4, 5), and unprecedented pressure to increase grain production (5, 6) to feed the growing number of people (7). In more developed countries/regions, such as the EU and China, high inputs of synthetic agrochemicals have been used to increase crop production—a typical farming practice since the "Green Revolution" (8). Increasing grain production with high inputs is costly and, more importantly, has negative eco-environmental consequences (9, 10). In China, for example, excessive use of synthetic N fertilizers has increased greenhouse gas emissions (11), lowered nutrient use efficiencies (8), and increased the risk of soil acidification (12) and water and soil pollution (13). The concept of globalization suggests that industrialized countries with more farmland, such as Australia, Canada, and the United States, could convert some permanent grasslands to cropland to produce more grain for international trade to feed the hungry, but doing so may result in carbon losses with environmental risks (14). Players along the food chain have suggested that sustainable cropping strategies are needed (8) to enable smallholder family farms to increase crop yields and narrow yield gaps (15), enhance farm net returns to improve livelihoods (15, 16), and enhance resource use efficiencies to minimize environmental impacts (9).

Developing integrated cropping systems by engaging researchers, extension personnel, and farmers is an effective approach for achieving these goals (10). Intercropping—a practice involving multiple crop species cultivated simultaneously in a single field as an alternative to conventional monoculture cropping—offers multiple benefits including boosting crop productivity (17), promoting rhizosphere processes to increase soil nutrient availability (18), maintaining the stability of soil chemical and biological properties (19), and enhancing multiple agroecosystem services (20). In northern China, staple crops, including spring wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and dry pea (*Pisum sativum* L.), are typically produced using conventional one-crop-per-year monocultures that occupy about 90% of the cropland (21). A shift to a two-crops-per-year relay planting system could have significant, positive socioeconomic impacts. However, the environmental benefits of relay planting need to be identified to incentivize farmers to adopt sustainable cropping systems.

In this study, we developed a "system integration" model that incorporated four key cropping practices in an integrated system (Fig. 1): 1) crops grown in a "0.5 + 0.5 relay planting" configuration,

Significance

The world has been struggling to find sustainable ways to increase crop production to satisfy the needs for food, feed, fiber, and industrial uses while reducing negative environmental impacts. This challenge is magnified in countries/regions where the availability of farmable land for agriculture is limited. We developed an integrated cropping system that incorporates key farming tactics. Tested in 16 field experiments over 12 consecutive years (2006 to 2017), the integrated system increased crop yields while decreasing the environmental footprint. The integration enables significant synergies in biophysical processes to occur under a wide range of crop inputs, suggesting that system integration can be adopted globally for a range of smallholder farming.

Author contributions: Q.C. designed research; Q.C., C.Z., A.Y., Y.W., and F.H. performed research; J.A.C., K.H.M.S., and L.W. contributed new reagents/analytic tools; C.L., L.W., and Y.G. analyzed data; T.N. provided tools to perform the "life cycle assessment"; C.L. completed carbon footprint calculations with Y.G.; J.A.C. and L.W. provided methods for analysis and interpreted the multiple-year data; K.H.M.S. provided the ideas/concept on how to interpret the results and bring the paper to a higher level/global perspective; and Q.C., L.W., and Y.G. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission. C.G. is a guest editor invited by the Editorial Board.

[1]To whom correspondence may be addressed. Email: chaiq@gsau.edu.cn, wangl@gsau.edu.cn, or UBC_Soil@outlook.com.

[2]Present address: Agroecosystems, the μBC-Soil group, Tallus Heights, Kelowna, BC V4T 3M2, Canada.

This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2106382118/-/DCSupplemental.

Published September 13, 2021.

in which an earlier-maturing, cool-season crop (primarily pea or spring wheat) is "relay-planted" with a later-maturing, warm-season crop (primarily maize) in alternate strips in the field, forming "pea + maize" or "wheat + maize" relay-planting patterns; 2) two relay crops, each occupying one-half of the land in a 0.5:0.5 ratio, are rotated in subsequent years (i.e., cool-season crops are planted in warm-season strips and vice versa) to create a "within-field strip rotation" that captures rotational benefits; 3) straw of the cool-season crop is left on the soil surface at harvest to cover the soil, while plastic film is applied to cover soil in maize strips to increase early-season soil temperatures to promote seedling establishment (22); and 4) the use of no-till or reduced tillage (i.e., one tillage operation for seedbed preparation prior to sowing) in crop production. The integrated system was tested under a wide range of inputs (*SI Appendix*, Table S1); during the 12 y, growing season precipitation ranged from 27 to 263 mm, and crops received 55 to 600 mm irrigation and 0 to 450 kg $N \cdot ha^{-1}$ annually.

A total of 16 field experiments were conducted across 12 y (2006 to 2017) in northwestern China (*SI Appendix*, Fig. S1). Details of the treatment structure are described in *Materials and Methods*, and the experimental units and input specifics are summarized in *SI Appendix*, Table S1. We tested the hypothesis that system integration achieves three goals—simultaneously increasing grain production, enhancing farm net returns, and decreasing carbon footprints and that the magnitude of these effects varies with the level of inputs. We aimed to determine whether the integrated relay-planting system was superior to conventional monoculture at a system level, unlike conventional studies that typically determine the effects of individual factors but not whole-system synergies. We measured grain and biomass yields, land-use efficiencies, farm net returns, and carbon footprint per product (i.e., per ton of grain, ton of biomass, and unit of net return) at a system level. The 16 field experiments covered a range of treatment factors and various input levels with different experimental units. We used the subgrouping effect of meta-analysis (23) to standardize the paired comparisons between relay-planting and monoculture systems, unlike multitudinous meta-analyses in the literature in which different outsourced "studies" are compiled to produce an outcome. We used Q and P values and i^2 and Tau^2 as the main assessors to determine treatment differences and their significance, along with ANOVA and linear and nonlinear

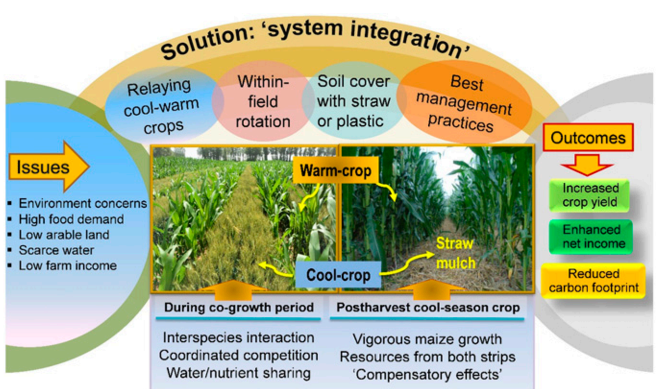

Fig. 1. A schematic illustration of system integration from issues to outcomes. The model incorporates key farming components in an integrated system, providing significant synergies for the whole system. The system integration offers several benefits, including coordinated competition between relay crops, enhanced interspecies interaction, and water/nutrient sharing between relay crops during the cogrowth period. Benefits to the warm-season crop following harvest of the cool-season crop include vigorous growth and use of resources from both strips, generating compensatory effects. As a result, system integration increases crop yield, enhances farm net returns, and decreases the carbon footprint.

regressions. The systematic analysis of the results across the 16 experiments depicts the outcome of the whole system integration rather than individual cause–effects.

Results

System Integration Increases Productivity and Net Returns. Averaged across the 16 experiments, sole-planted monoculture pea, wheat, and maize produced grain yields (on a dry basis) of 3.65, 6.51, and 12.43 $t \cdot ha^{-1} \cdot yr^{-1}$, respectively, while pea + maize and wheat + maize relay systems yielded 11.41 and 13.84 $t \cdot ha^{-1} \cdot yr^{-1}$, respectively. The "yield advantage" model (Eq. **1**, in *Materials and Methods*) quantified the percent difference between the two systems; the relay systems increased grain yields by 29.1% for the cool-season crops (pea and wheat) and 49.5% for the warm-season crop (maize) (Figs. 2*A* and 3 *A* and *B*). Similarly, relay-planting increased straw biomass by 24.6% for the cool-season crops and 37.7% for the warm-season crop. Standardized paired comparisons across treatments/replicates (n = 480) revealed the absolute differences in values between the two systems (Table 1 and *SI Appendix*, Fig. S2 *A–F*); relayed cool-season crops increased grain yields by 1.78 $t \cdot ha^{-1}$ and straw biomass by 2.12 $t \cdot ha^{-1}$, and relayed maize increased grain yields by 6.06 $t \cdot ha^{-1}$ and straw biomass by 7.79 $t \cdot ha^{-1}$. As a result, net returns increased by US$708 $\cdot ha^{-1}$ for relayed cool-season crops and US$1793 $\cdot ha^{-1}$ for relayed maize, representing a 27.9 and 49.1% improvement in net returns, respectively, relative to the corresponding sole crop (Fig. 3*C*).

System Integration Lowers Carbon Footprint. Following the Climate-Smart Feedback guidelines of the Intergovernmental Panel on Climate Change (24), we calculated the carbon footprint of the different cropping systems in three matrices, i.e., 1) per unit of grain produced per hectare per season (kg $CO_2eq \cdot t^{-1}$ grain), 2) per unit of straw biomass (kg $CO_2eq \cdot t^{-1}$ biomass), and 3) per unit of net return (kg $CO_2eq \cdot$ US$100^{-1} net return) (Eqs. **2** and **3** in *Materials and Methods*). On a percentage basis, relay systems decreased the carbon footprint by an average of 20.5% per unit of grain, 11.7% per unit of biomass, and 21.8% per unit of net return ($P < 0.01$) relative to sole cropping (Fig. 2*B*). More specifically, the pea + maize relay system decreased the carbon footprint per yield, per biomass, and per net return by 5.4%, 0.8%, and 8.2%, respectively (Fig. 3 *D–F*); the corresponding values for the wheat + maize relay system were 29.8%, 17.7%, and 31.2%, respectively. On an absolute value basis, the cool-season crops decreased the carbon footprint by 30.9 kg $CO_2eq \cdot t^{-1}$ of grain, 13.0 kg $CO_2eq \cdot t^{-1}$ of biomass, and 6.5 kg $CO_2eq \cdot$ US$100^{-1} of net return, across the 16 experiments (Table 1 and *SI Appendix*, Fig. S3 *A–F*); more significantly, the warm-season crop in the relay systems decreased the three matrices of carbon footprint by 134.0 kg $CO_2eq \cdot t^{-1}$ of grain, 62.0 kg $CO_2eq \cdot t^{-1}$ of biomass, and 42.9 kg $CO_2eq \cdot$ US$100^{-1} of net return, relative to sole maize.

Calculated on the basis of per hectare per season, sole pea, wheat, and maize emitted 1,334, 2,661, and 4,747 kg $CO_2eq \cdot ha^{-1} \cdot season^{-1}$, respectively, while the pea + maize and wheat + maize relay systems emitted 3,479 and 4,022 kg $CO_2eq \cdot ha^{-1} \cdot season^{-1}$, respectively. These values, based on all treatments in the 16 field experiments, show that "cool + warm" season relay-planting emitted significantly more greenhouse gases per season per area of farmland than the cool-season crops in monoculture but significantly less than maize in monoculture.

Interactions among Outcome Factors. The increased annual net returns with the relay-planting system, relative to conventional monoculture practices, were primarily due to increased crop yields per unit of farmland (Fig. 4*A*), in which the two parameters (net returns and yield) had a positive linear relationship across productivity levels (Fig. 4*B*). Smallholder families mostly rely on farm

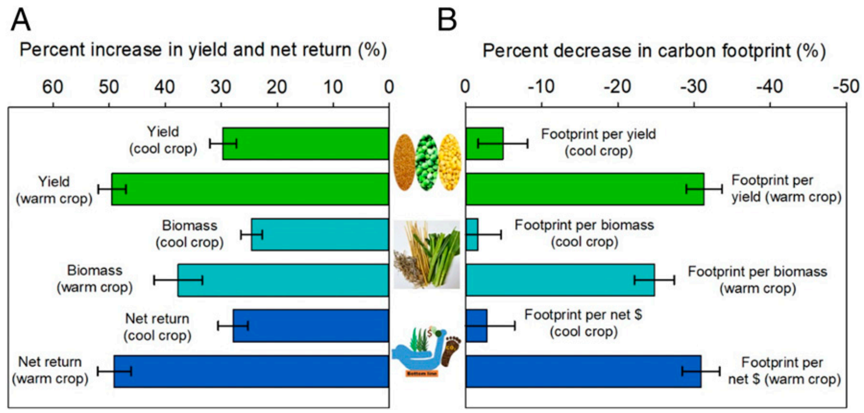

Fig. 2. Percent differences in (*A*) productivity (yield, biomass, net return) and (*B*) the three matrices of carbon footprints between monoculture and relay-planting systems. The percentages are based on 480+ field replicates across 16 experiments (detailed in *SI Appendix*, Table S1), with the effect size standardized across treatments using the subgrouping effect of meta-analysis (23).

income for their livelihoods. The positive outcomes of system integration indicate the importance of focusing on increasing crop productivity per area of land to enhance the livelihood of farm families.

Irrigation and fertilization are two major inputs for crops in the arid and semiarid areas of northwestern China (25, 26), where annual evaporation (>2,400 mm) is nearly 10 times the annual precipitation (50 to 250 mm) (27) and soil organic matter is typically less than 1.5% (28). Both crop yield and greenhouse gas emissions increased linearly with increased irrigation from 60 to 720 mm (Fig. 5*A*), in which the emissions associated with irrigation were mainly due to the consumption of diesel fuel and electricity for pumping water from underground. Crop yields increased at a faster rate than emissions, as reflected in the slopes of the linear regressions (21.828 for yield versus 7.301 for emissions). In contrast, grain yield and fertilizer N rate had a cubic relationship (Fig. 5*B*), in which crop yield increased sharply as N rate increased from 75 to 325 kg N · ha^{-1} before leveling off with further increases in N fertilization. However, greenhouse gas emissions had a positive linear relationship with fertilizer N rate (Fig. 5*B*). These results indicate that high inputs in irrigation and N fertilizer will increase emissions but not necessarily increase productivity.

Mechanisms for Achieving Multiple Goals with System Integration. The biological mechanisms responsible for significantly increasing yield and net returns and decreasing the carbon footprint with system integration are not clear. However, the results of the 16 experiments across 12 y, along with other relevant studies (21, 29, 30), suggest that the following four mechanisms are responsible for the favorable outcomes:

Enhanced water and nutrient use efficiencies. The spatial and temporal arrangement of two crops with contrasting growth habits in neighboring strips enhanced water and N use efficiencies, leading to increased land-use efficiency. On average, the relay systems increased water use efficiency (kilogram grain per millimeter of precipitation plus irrigation) by 13.6% (Fig. 6*A*) and fertilizer N use efficiency (kilogram grain per kilogram fertilizer N supplied) by 35.2% (Fig. 6*B*), relative to the corresponding sole crop. As a result, the land equivalent ratio (Eq. **4**) reached 1.32 for relay systems in response to irrigation (Fig. 6*C*) and 1.29 in response to N fertilization (Fig. 6*D*), both significantly greater than the breakeven point (a value of 1.0). These results suggest that the volume of grain produced on 100 ha of farmland with the relay-planting system would require 130 ha of equivalent land under traditional sole cropping, representing a 30% increase in land-use efficiency.

Promoted belowground interspecies interaction. Niche differences in root structure and rooting depth profile in relay planting promoted belowground interspecies interactions and generated a "root overlay effect" (Eqs. **5**–**7**). The 3-y "root barrier" experiments (detailed in *Materials and Methods*), designed to quantify the outcome of underground interspecies interaction (Eq. **8**), revealed that the "full-sharing" treatment in the relay system increased root dry weight by 53% for the cool-season crops and 67% for the warm-season crop, relative to the "no-sharing" treatment that mimics conventional sole cropping (Table 2); this increased the root-to-grain ratio by 23 and 42% and root-to-straw ratio by 40 and 33% for the intercropped cool- and warm-season crops, respectively. The improved rooting systems enhanced nutrient uptake and between-crop nutrient exchange activity. Indeed, the improved rooting system of pea in the pea + maize system promoted nodulation, which increased the amount of N symbiotically fixed from the atmosphere (Eq. **9**) by 36%, seed N content by 34%, and straw N content by 23%, relative to sole pea (Table 3). Also, the relayed maize in the pea + maize system had 9% more N in aboveground tissues than monoculture maize.

Relaying crops with contrasting rooting profiles promoted nutrient mobilization in rooting zones and encouraged nutrient sharing between relayed plants (21). The case was strong when a nutrient-mobilizing crop was relay-planted with a non-nutrient-mobilizing crop in strips, often promoting the availability of some macronutrients [e.g., phosphorus (P)] (Fig. 7*A*) and micronutrients (e.g., iron and zinc) (Fig. 7*B*). In the example, P-mobilizing plants mobilized sparingly soluble inorganic P in soil by exuding carboxylates and protons, or hydrolyzed soil organic P by microbial or root-released phosphatase enzymes into soluble inorganic P (Fig. 7*A*), making them available for the intercropped plants that lack P-mobilizing capacity. Also, some micronutrients, such as iron (Fe) and zinc (Zn), which are generally less soluble in soils, were enhanced by intercropping (Fig. 7*B*), in which available Fe increased for dicotyledonous species and Zn increased in Zn-impoverished soils.

Generated "compensatory effects." The coordination of resource use between relayed crops generated "compensatory effects" for warm-season maize. After the harvest of the cool-season crop, relayed maize grew vigorously using accessible resources in both field strips and experienced compensatory effects for 1) soil water availability, 2) aboveground plant dry matter accumulation and remobilization from vegetative tissues to grain, and 3) root dry matter accumulation, as follows:

Soil water compensation. In the pea + maize relay system, the unused water left in the strips after the relayed pea had been harvested provided timely compensation for the rapidly growing maize. The 3-y aforementioned root barrier experiment quantified the soil water compensatory effect (Table 4). Postharvest relayed

https://doi.org/10.1073/pnas.2106382118

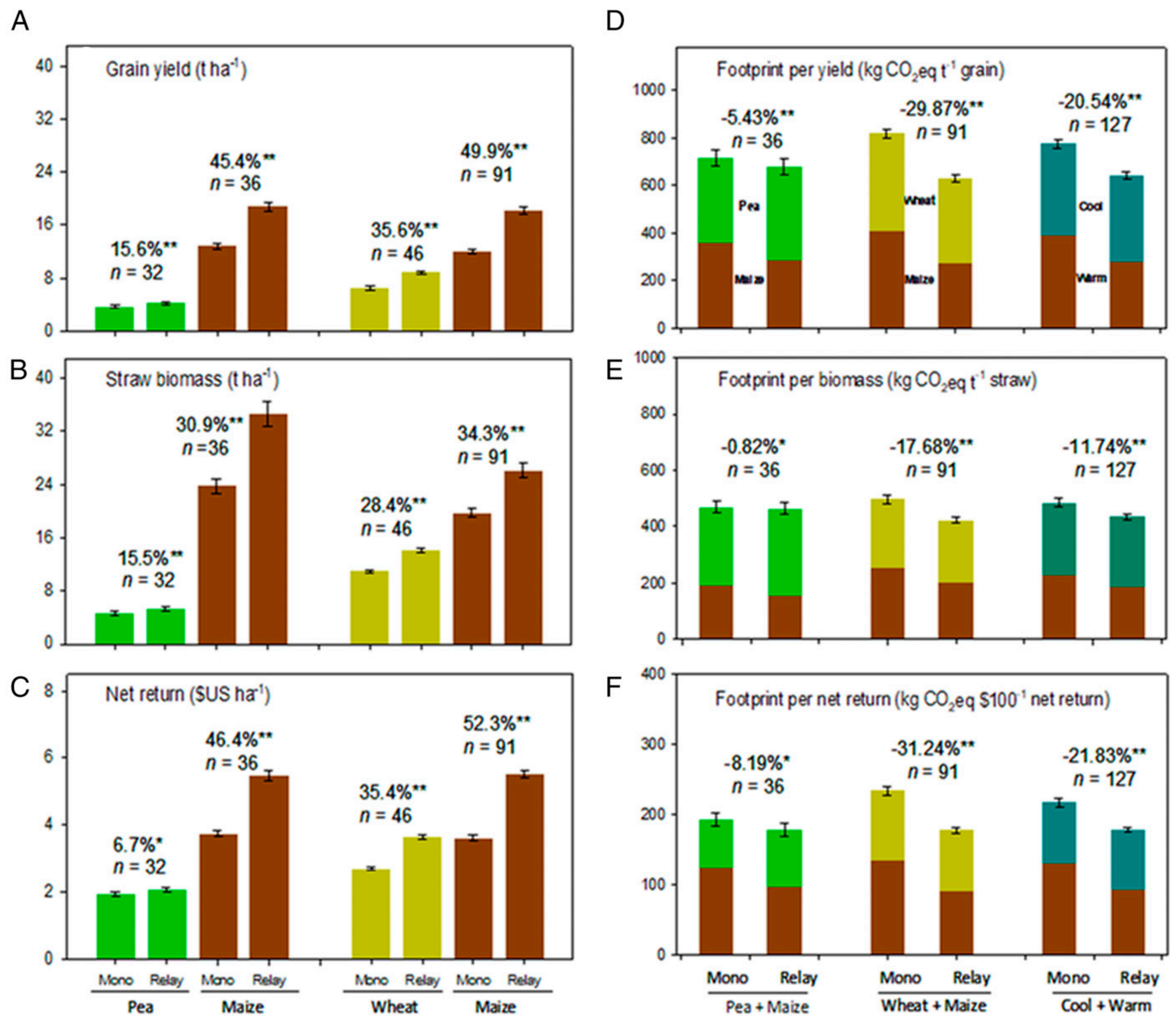

Fig. 3. Crop productivity and carbon footprints of monoculture versus relay-planting systems. (*A*) Grain yield, (*B*) straw biomass, and (*C*) net returns for monoculture pea, monoculture maize, and monoculture wheat, relative to pea + maize and wheat + maize relay planting. The carbon footprint was determined per unit of (*D*) grain yield, (*E*) straw biomass, and (*F*) net return. Percentages in each pair of bars denote mean differences between monoculture and relay planting, *n* represents the number of paired comparisons, and * and ** denote that the mean difference between pairs is significant at $P \leq 0.05$ and $P \leq 0.01$, respectively.

pea and relayed maize in the full-sharing treatment had an average of 36 mm more water than monoculture maize, while maize in the no-sharing treatment experienced a water deficit of 33 mm. Also, the relay system allowed the early-sown pea crops to use soil water preserved from snow accumulation during the winter that melts in early spring, and available soil water in both soil strips compensated for the water demands of the vigorously growing maize after the cool-season crop had been harvested. Overall, supplementary irrigation to crops is quite high in the experimental area due to high evapotranspiration and low precipitation. Without irrigation, little crop production would occur in this region. However, total water use by relay-planting systems is typically higher than sole cropping; thus, more sophisticated water-saving techniques (31), such as deficit irrigation (27), are needed to alleviate the challenge of water shortage in arid and semiarid areas.

Dry matter compensation. The root barrier study showed that the growth of relayed maize increased substantially after pea was harvested, evidenced by the higher plant growth rate (PGR) relative to sole maize (Eqs. **10** and **11**). In the pea + maize system, relayed maize increased PGR during the silking–filling period by 116, 125, and 170%, relative to monoculture maize, at low, medium, and high maize plant densities, respectively, at a medium rate of N fertilizer (data not presented); at a low rate of N fertilizer, the corresponding increases in PGR were 156, 200, and 195%, respectively. Across treatments (N rates, maize plant densities, and years), relayed maize increased PGR by an average of 70% during tasseling–silking, 159% during silking–filling, and 155% during filling–hard dough, relative to sole maize.

Root growth compensation. Averaged across 3 y (2014 to 2016), relayed maize had 78% more root dry matter, 91% higher root length density, and 18% greater root surface area density than sole maize. The increased root growth and biomass were largely due to belowground interspecies interactions, which promoted soil water and nutrient sharing between relayed crops. The root barrier experiment revealed that the root biomass of maize in the full-sharing treatment was 143 and 210% greater than the partial-sharing

Table 1. Means of grain yield, biomass, net return, and their carbon footprint per unit of product

Model	No. pairs*	Effect size and 95% CI			Test of null (two-tailed)		Heterogeneity				
		Mean	Lower limit	Upper limit	*Z* value	*P* value	*Q* value	df (*Q*)	*P* value	I^2	Tau^2
Grain yield (kg · ha^{-1})											
Cool-season	41	1,776.1	1,509.6	2,042.6	13.1	0.000	5,265	40	0.000	99.2	837.2
Warm-season	41	6,039.9	5,320.4	6,759.4	16.5	0.000	2,587	40	0.000	98.5	2,229.4
Straw biomass (kg · ha^{-1})											
Cool-season	41	2,121.8	1,867.2	2,376.5	16.3	0.000	2,207	40	0.000	98.2	712.1
Warm-season	41	7,794.4	5,987.1	9,601.7	8.5	0.000	2,466	40	0.000	98.4	5,698.6
Net return (US$ · ha^{-1})											
Cool-season	41	707.8	572.8	842.8	10.3	0.000	3,659	40	0.000	98.9	426.7
Warm-season	41	1,790.8	1,557.3	2,024.3	15.0	0.000	1,491	40	0.000	97.3	721.0
Carbon footprint per yield (kg CO_2eq · t^{-1} grain)											
Cool-season	40	−30.9	−55.0	−6.8	−2.5	0.012	3,269	39	0.000	98.8	74.4
Warm-season	40	−134.0	−151.0	−117.1	−15.5	0.000	1,604	39	0.000	97.6	51.0
Carbon footprint per straw biomass (kg CO_2eq · t^{-1} biomass)											
Cool-season	38	−13.0	−27.7	1.6	−1.7	0.081	1,496	37	0.000	97.5	42.8
Warm-season	41	−62.0	−74.0	−50.0	−10.1	0.000	2,039	40	0.000	98.0	35.7
Carbon footprint per unit of net income (kg CO_2eq · US$100^{-1} return)											
Cool-season	38	−6.5	−12.7	−0.4	−2.1	0.037	2,854	37	0.000	98.7	18.3
Warm-season	38	−42.9	−43.9	−41.9	−85.3	0.000	640	37	0.000	94.2	13.5

*Standardized pairs between the monoculture and relay cropping systems across treatments.

and no-sharing treatments, respectively. Variation partitioning analysis revealed that belowground interspecies interactions contributed 143% to increased root biomass in relayed maize, of which water and nutrient sharing contributed 80% and compensatory effects due to root overlapping contributed 35%.

Enhanced coordination in competition for resources. In the relay system, cool-season crops were planted 2 to 3 wk earlier than relayed maize, providing a competitive advantage for the earlier-sown crops due to greater soil moisture in the early spring. We developed two terms—relative competitiveness (*Cr*) (Eq. **12**) and aggressiveness (*Ar*) (Eqs. **13** and **14**)—to quantify the competitiveness between relayed crops. We found that *Cr* for relayed pea was 1.07%, 1.70%, and 1.29% during the early, middle, and late cogrowth periods, respectively, representing a 7 to 70% competitive advantage over relayed maize. Similarly, *Ar* for relayed pea ranged from 0.06 to 0.58 during the cogrowth period, representing 6 to 58% more aggressiveness in growth than relayed maize. In addition, relaying plants with contrasting architecture, morphology, and canopy created a "border effect"—a microenvironment that favors the effective use of aboveground (CO_2 and photosynthetically active radiation) and belowground (water, nutrient, and microbiome) resources.

Discussion

The integrated system was tested under a range of input levels (i.e., irrigation, fertilization, and precipitation) to represent various smallholder cropping systems. The outcomes of the 12-y studies across the 16 field experiments of various input levels show that system integration could benefit various types of smallholder farming globally. Simultaneously increasing crop yield and reducing environmental impact are primarily relatable to biophysical processes operating in the fields, including root penetration for soil water and nutrient sharing, rhizosphere interactions, and complementary effects in relay planting in which two crops are planted in alternate rows in the same field. The positive outcomes of the system from the wide range of inputs trialed suggest that the biophysical links within and between relay crops are likely to occur in a range of smallholder farming and that the system integration approach could be applied to many other smallholder systems worldwide, including high- and low-input farming.

Relay cropping is usually more labor intensive than sole cropping (32). In some regions, this is an issue when the costs of agricultural labor increase due to rising off-farm wages, leading to the migration of some young workers to cities for employment (33). However, various types of small-scale equipment suitable for system integration, including seeders for cereal and legumes, planters for maize, and harvesters for relayed crops, have been made available for smallholder farms (*SI Appendix*, Fig. S4 *A–D*). This has alleviated many potential issues associated with labor shortages in rural communities (33). In addition, education for technology adoption has been provided to farmers and agribusiness personnel through various means, including classroom training, field tours, demonstrations, and the engagement of researchers and educators with farmers (*SI Appendix*, Fig. S4 *E–H*), increasing smallholders' confidence in adopting relay-planting systems. The incentive for adopting the integrated cropping system is driven primarily by the benefits of increased productivity and net returns. Official records for areas sown to different cropping systems in China often lack detail, but available sources suggest that smallholders are rapidly adopting the relay-planting system in northwestern China. For example, the pea + maize relay system has increased substantially in some regions, such as Wuwei county, Gansu province, due to the symbiotic benefit of atmospheric N_2 fixation by pea plants that enables farmers to reduce synthetic N fertilizer use.

Intercropping, such as cereal–cereal and cereal–legume, has been used in many areas of the world to improve crop yields (17, 34), resource use efficiencies (35, 36), and agroecosystem services (37). However, few studies have shown how intercropping affects the environmental footprint. Conventional farming uses excessive synthetic chemicals to boost crop yields, which often have a negative environmental impact. In the system integration model, we developed key cropping components—including relay planting, within-field rotation, reduced tillage, soil mulching and straw cover, and best agronomic practices—that are incorporated in an integrative manner. The significant, positive outcomes from the synergies of system integration are not seen in conventional cropping.

Food security has been a major concern worldwide (38, 39) and is a significant issue for the livelihood of rural communities in highly populated regions and countries (38, 39). For example, in Africa and some southeastern Asian regions, the lack of resources

https://doi.org/10.1073/pnas.2106382118

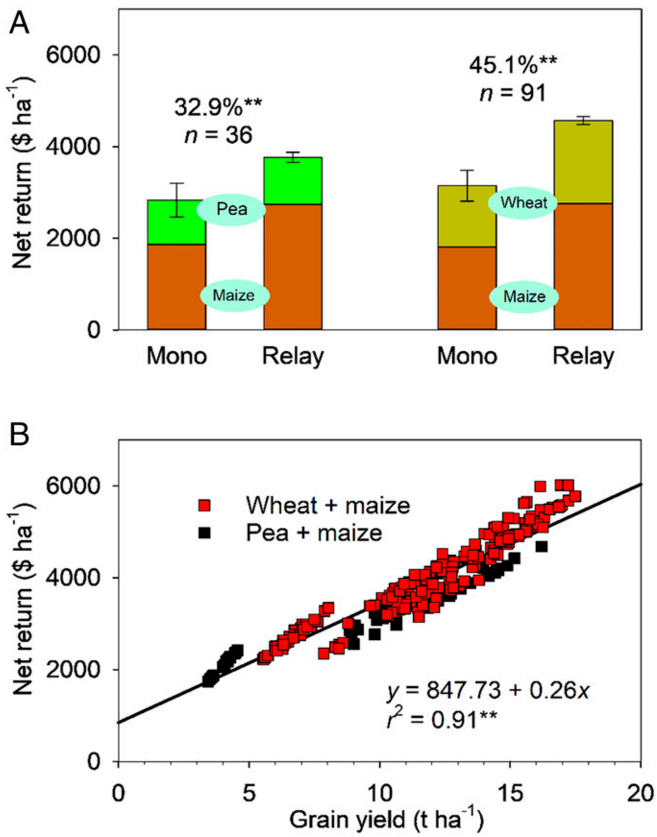

Fig. 4. Net return in relation to grain yield. (*A*) The integrated relay systems increased net returns by 33 to 45% over monoculture (mono) across the multiple treatments tested in 16 field experiments (detailed in *SI Appendix*, Table S1). (*B*) Increased net returns were largely due to increased crop yield. The percentages in *A* denote mean differences between monoculture and relay systems, *n* represents the number of paired comparisons, and ** in *A* and *B* denotes significance at $P \leq 0.01$.

and finances for needed equipment and supplies is a major constraint for agricultural development (40, 41). In more developed areas, such as the Eastern European nations and China, excessive agrochemical inputs in crop production have caused serious eco-environmental concerns (8, 42). An added challenge for agriculture is the uncertainty of the consequences of climate change and unpredictable abiotic stresses, which put pressure on agriculture to produce affordable food in sufficient quantities with minimal negative impact on the environment (7, 41). Policymakers, scientists, and key players along the grain-to-food chain have been working to establish strategies to alleviate these challenges, such as the United Nation's Climate-Smart Agriculture strategies and "conservation agriculture" policies. However, as is often the case, there is much talk and little action in the real world of farming. Our study demonstrated that system integration is an effective way to increase crop yields and net farm income while concurrently reducing the emission footprint per farm product. This example of system integration could serve as a model to face these challenges. A cross-globe approach may be required to test whether our integrated system performs similarly in other regions of the world. The consistent results from the 16 field experiments indicate the potential for integrated relay-planting systems to be adopted in areas such as the cooler highlands of eastern and southern Africa, the mountainous regions of southern and central Asia, and the Andes region of South America, as climates in these areas resemble the semiarid temperate characteristics of northwestern China.

Materials and Methods

Site Description. A total of 16 field experiments were conducted from 2006 to 2017 at the Agricultural Research and Education Station of Gansu Agricultural University in Wuwei (37°56′ N, 102°38′ E, altitude 1,520 m), Gansu province (*SI Appendix*, Fig. S1). This location is in the eastern part of the Hexi Corridor of northwestern China in the temperate arid zone of the center of the Eurasian continent, a typical arid region with a harsh growing environment and declining agricultural land area. At this site, long-term (1960 to 2015) solar radiation in a crop growing season averages 5.67 kWh · m^{-2} · d^{-1}, annual sunshine duration is 2,945 h, mean annual air temperature is 7.2 °C, accumulated air temperature above 0 °C is 3,513 °C, accumulated air temperature above 10 °C is 2,985 °C, and the frost-free period is 156 d. These natural conditions (especially light and heat) are more than sufficient for one crop per year but insufficient for two crops per year. Thus, relay planting

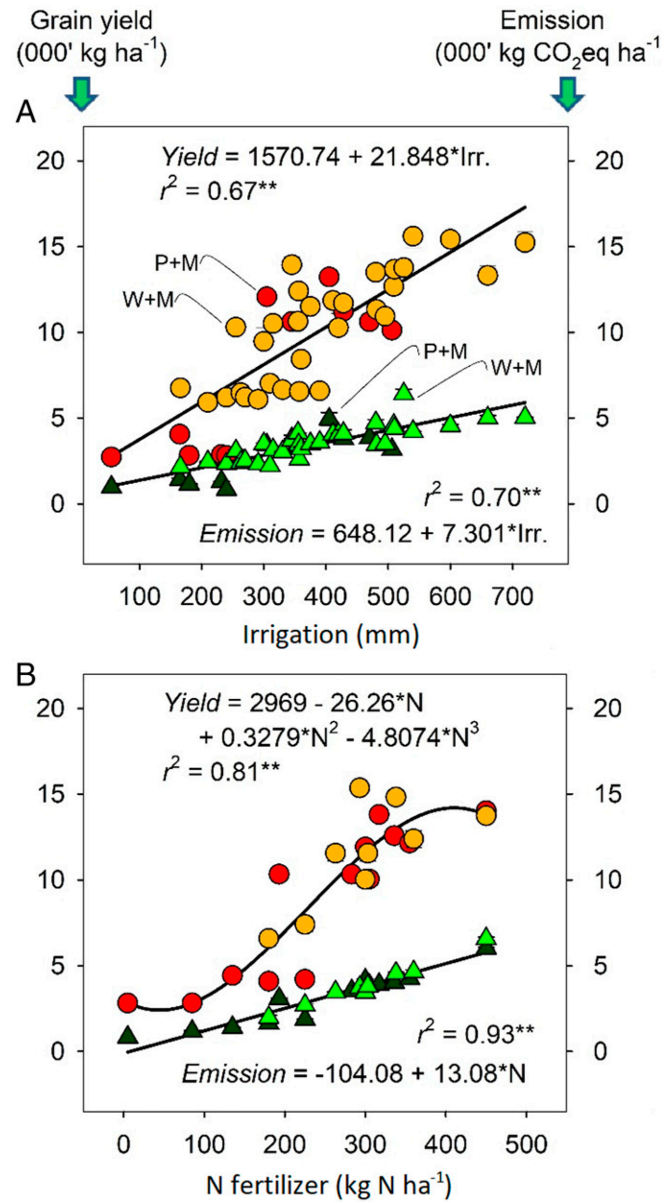

Fig. 5. Crop yield and greenhouse gas emissions in relation to (*A*) irrigation and (*B*) fertilization. Grain yield and emission in pea + maize (P+M) and wheat + maize (W+M) relay systems respond linearly to (*A*) irrigation amount (mm), but (*B*) grain yield responded to N fertilizer rate in a cubic relationship, while emissions responded to N rate linearly. Emissions associated with irrigation are mainly due to the consumption of electricity for pumping underground water. ** following the r^2 values denotes the regression models significant at $P \leq 0.01$.

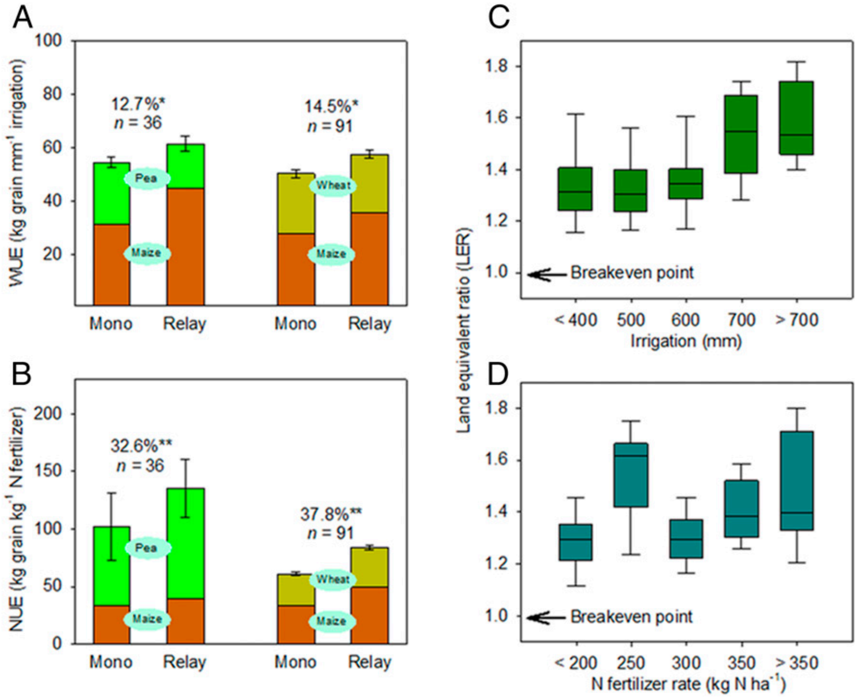

Fig. 6. Water- and nitrogen-use efficiencies and LER for relay systems relative to monoculture. Relay planting increased (*A*) water use efficiency (WUE) by 12.7% for pea + maize and by 14.5% for wheat + maize systems, relative to monoculture, and (*B*) nitrogen use efficiency (NUE) by 32.6 and 37.8%, respectively. The relay systems had an average LER of (*C*) 1.32 across irrigation strategies and (*D*) 1.30 across N fertilizer rates. An LER value greater than 1.0 (the "break-even point") represents an advantage in land-use efficiency for the relay system relative to monoculture. The average LER of 1.30 indicates that the quantity of the grain produced on 100 ha of farmland with the relay systems would require 130 ha with conventional monoculture systems, a 30% increase in land-use efficiency. The percentages in *A* and *B* denote mean differences between monoculture and relay planting, *n* represents the number of paired comparisons, and * and ** denote that the mean difference is significant at $P \leq 0.01$ and $P \leq 0.01$, respectively.

an earlier-maturing, cool-season crop with a later-maturing warm-season crop enables to use the available light and heat resources more effectively. The mean annual precipitation at this site ranges from 50 to 155 mm, mostly from June to September, while evaporation is typically >2400 mm (31). Thus, irrigation is required for crop production (27). The soil is classified as an Aridisol, with soil bulk density in the 0- to 110-cm soil layer averaging 1.44 $g \cdot cm^{-3}$ and soil organic carbon in the 0- to 15-cm soil layer <12 $g \cdot kg^{-1}$.

Experimental Design. Two relay systems, pea + maize and wheat + maize, along with sole pea, sole wheat, and sole maize, were arranged in randomized complete block designs with three or four replicates per experiment. For the pea + maize and wheat + maize relay systems, a strip of six rows of cool-season pea or wheat (20-cm row spacing) was alternated with a strip of two to three rows of warm-season maize (60-cm row spacing). An example of the strip planting is illustrated in *SI Appendix*, Fig. S5. Within a year, the two intercrops were planted alternately in the neighboring strips; in successive years, the two intercrops were planted on each other's stubble from the previous year. For instance, the 2017 wheat crop was planted on the 2016 maize stubble, while the 2017 maize was planted on the 2016 wheat stubble. The planting of the two intercrops in alternate strips in the same year and on alternate stubbles in successive years created a within-field rotation. The cool- and warm-season crops each occupied one-half of the land area in a 0.5:0.5 ratio. Plots were 4.8 to 7.8 m wide and 8 to 10 m long, depending on the experiment. Thus, each plot accommodated three to four sets of relayed alternate strips. The straw of the cool-season crop was left on the soil surface at harvest to mulch the soil, while plastic film was applied to cover the soil in all maize crops. All crops (relayed and monoculture) were planted using minimal tillage practices and managed using the best agronomic practices adopted in the local area.

A total of 16 field experiments were conducted to test relay-planting systems and the corresponding monoculture crops under various treatments (*SI Appendix*, Table S1), such as rate of N fertilizer, irrigation amount, mulching practices with plastic film or crop straw, and maize planting density. These treatments were designed to determine the possible mechanisms involved in the advantage of relay planting compared to monoculture cropping.

Plot Management. Pea and wheat were planted in the first 2 wk of April and harvested by early to mid-July. Maize was planted 2 to 3 wk after the cool-season crops were planted and harvested in the final week of September. In each experiment, inorganic N (ammonium nitrate) and P (monoammonium phosphate) fertilizers were used for all crops, with the amounts varying among some treatments and years (*SI Appendix*, Table S1). The P fertilizer was broadcast and incorporated to 20-cm soil depth using rotary tillage. For N fertilizer application in maize, 50% of the N was sidebanded at sowing, with the remaining N applied by hand at the stalk elongation stage. For pea and wheat, all N fertilizers were applied to the side of the seed rows at 10 cm depth. Because effective commercial *Rhizobium* inoculant is not available in China, pea was not inoculated with *Rhizobium* but fertilized with the amount detailed in *SI Appendix*, Table S1. No potassium (K) or sulfur (S) fertilizers were applied, as the soil contained 350 to 560 $kg \cdot ha^{-1}$ K and 50 to 85 $kg \cdot ha^{-1}$ S, sufficient for the crops involved.

Irrigation was applied to the crops using a "ridge–furrow irrigation" method (22), with a ridge (40 cm wide × 30 cm high) between neighboring plots to prevent water movement between plots. In some experiments, alternate-row irrigation—a deficit irrigation strategy (27)—was compared with ridge–furrow irrigation (*SI Appendix*, Table S1). At each time of irrigation, the amount of water flowing to each plot was recorded using a flow meter installed at the recharging end of the plot.

Soil water content in various soil layers (0 to 30, 30 to 60, 60 to 90, and 90 to 120 cm) was measured at sowing and crop harvest each year. Soil water content in the 0- to 30-cm layer was measured using the oven-dry method, while those in the other layers (30 to 60, 60 to 90, and 90 to 120 cm) were measured using neutron probes (NMM system, model CPN 503 DR, Campbell Pacific Nuclear International Inc.). Two neutron probes per plot were installed about 10 d prior to sowing, with one probe installed between two cool-season (pea or wheat) plant rows and the other between two maize plant rows. Those probes remained in the same position in the plot throughout the entire experimental period. Evapotranspiration (ET) was

https://doi.org/10.1073/pnas.2106382118

Table 2. Root dry weight and the ratio of root to aboveground dry weight

Year	Root barrier treatment*	Root dry weight ($kg \cdot ha^{-1}$)†			Ratio of root dry weight to: Aboveground dry weight		Grain dry weight		Straw dry weight	
		Wheat	Maize	Total	Wheat	Maize	Wheat	Maize	Wheat	Maize
2014	Full-sharing	1,742	5,288	7,030	0.181	0.260	0.393	0.578	0.336	0.477
	Partial-sharing	1,568	3,990	5,558	0.178	0.204	0.403	0.451	0.319	0.377
	No-sharing	1,083	3,081	4,164	0.140	0.167	0.322	0.363	0.249	0.308
2015	Full-sharing	1,792	4,951	6,743	0.165	0.234	0.401	0.494	0.280	0.443
	Partial-sharing	1,383	3,399	4,782	0.133	0.167	0.350	0.365	0.216	0.307
	No-sharing	1,383	3,399	4,782	0.133	0.167	0.350	0.365	0.216	0.307
2016	Full-sharing	1,930	4,318	6,248	0.179	0.143	0.360	0.385	0.358	0.230
	Partial-sharing	1,493	3,895	5,388	0.134	0.181	0.301	0.363	0.243	0.369
	No-sharing	1,167	2,351	3,518	0.121	0.129	0.331	0.284	0.190	0.237
3-y mean	Full-sharing	1,821	4,852	6,674	0.175	0.212	0.384	0.486	0.325	0.383
	Partial-sharing	1,481	3,761	5,243	0.149	0.184	0.351	0.393	0.259	0.351
	No-sharing	1,320	3,275	4,595	0.136	0.172	0.288	0.380	0.258	0.320
% increase	'Full' over 'Partial'	23.0	29.0	27.3	17.8	15.3	9.5	23.6	25.3	9.2
	'Full' over 'No'	53.0	67.2	63.1	32.3	36.3	22.6	42.0	39.9	32.8

*Full-sharing: no root barrier inserted between crop strips, allowing roots of relay-planted crops to penetrate neighboring strips, promoting water and nutrient sharing between strips; partial-sharing: a nylon mesh barrier was physically inserted between crop strips in the 0- to 110-cm rooting zone, allowing water and nutrients to move freely between strips but no physical penetration between strips; no-sharing: a plastic sheet was physically inserted between crop strips, preventing soil resources from moving between strips.

†Averaged over 3 y, wheat root dry weight per volume (centimeters^{-3}) of soil in the full-sharing treatment was 45, 36, 231, 131, and 222% greater in the 0- to 20-, 20- to 40-, 40- to 60-, 60- to 80-, and 80- to 100-cm soil layers, respectively, relative to the no-sharing treatment; the corresponding values were 16, 16, 142, 63, and 78%, respectively, relative to the partial-sharing treatment. Maize root dry weights in the full-sharing treatment were 15.0, 15.8, and 36.5% greater in the 0- to 20-, 60- to 80-, and 80- to 100-cm layers, respectively, than those in the partial-sharing and no-sharing treatments, and there were no differences among treatments in the 20- to 40- and 40- to 60-cm layers.

determined using the equation ET = $P_r + I + \Delta S + W_g - R - D$, where P_r is effective precipitation, I is the irrigation quota, ΔS is the change in soil water content for a given soil layer during the growth period, W_g is the amount of water used by crops through capillary rise from groundwater, R is surface runoff, and D is deep drainage below the root zone. Capillary rise at the experimental site was considered negligible because the water table is deeper than 40 m (31). Runoff never occurred because each plot was edged with a ridge.

Crop Yield and Land Equivalent Ratio. At maturity, all plants in each plot were harvested using a plot harvester (*SI Appendix*, Fig. S4). Grain and straw were cleaned, air-dried, and weighed and then converted into dry weight based on moisture content in the sample. For example, 100 kg air-dried grain with a 12% moisture content was converted to 88 kg grain dry mass in the sample. All yields presented below refer to dry mass.

The yield advantage of each component crop in the relay system over their corresponding monoculture crop was quantified using the yield advantage equation:

$$\text{yield advantage (\%)} = \frac{Y_{rel} - Pr \times Y_{mono}}{Pr \times Y_{mono}} \times 100, \quad [1]$$

where Pr is the proportion of land area that a component crop occupies in the total relay-planting area, Y_{rel} is yield of the relay-planted crop, and Y_{mono} is yield of the corresponding monoculture crop. The yield advantage of relay planting is assessed as percent increase or decrease in yield relative to the corresponding monoculture crop.

Calculation of Financial Return. The amount of each crop input (fertilizer, pesticide, seed, mulching material for maize, and fuel in various operations) was recorded for each treatment in each year. The cost per unit of input was sourced from the China Yearbook of Agricultural Price Survey (43) for each of the 12 experimental years and averaged across years when calculating net returns.

Emission Estimate and Footprint Calculation. Greenhouse gas emissions were estimated using a country-specific approach with field-measured emission factors (EFs) from semiarid northern China coupled with empirical modeling (Eqs. 2 and 3), an effective approach widely adopted by scientific communities (44, 45). Site-specific EFs were established to adequately quantify emissions from croplands (46). Here, emissions (kg $CO_2eq \cdot ha^{-1}$) using the northwest China–specific approach were estimated as:

$$CO2eq_{SFN} = Q_{SFN} \times \{(FRAC_{GASF} \times EF_{VD}) + EFSFN + (FRAC_{LEACH} \times EF_{LEACH})\} \times \frac{44}{28} \times 298 \quad [2]$$

$$CO2eq_{RES} = Q_{RES} \times \{(EFRES + FRAC_{LEACH} \times EF_{LEACH})\} \times \frac{44}{28} \times 298, \quad [3]$$

where CO_2eqSFN and CO_2eqRES are total N_2O emissions from synthetic N fertilizer application and crop residue decomposition (kg $CO_2eq \cdot ha^{-1}$), respectively, Q_{SFN} is the quantity of synthetic N fertilizer applied (kg $N \cdot ha^{-1}$), Q_{RES} is the quantity of crop residue N, $FRAC_{GASF}$ is the fraction of inorganic fertilizer N that volatilized as NH_3- and NO_x-N, EF_{VD} is the N_2O EF for volatilized NH_3- and NO_x-N ($EF_{VD} = 0.01$ kg N_2O-N $\cdot$ kg^{-1} N), EF_{LEACH} is the N_2O EF for nitrate leaching ($EF_{LEACH} = 0.0075$ kg N_2O-N $\cdot$ kg^{-1} N), EF_{SFN} is the N_2O EF from synthetic N application (kg N_2O-N $\cdot$ kg^{-1} N), EF_{RES} is the N_2O EF from crop residue N (kg N_2O-N $\cdot$ kg^{-1} N), 44/28 is the conversion coefficient from N_2O-N to N_2O, and 298 is the global warming potential of N_2O for the 100-y time frame of climate-carbon feedbacks (24).

Direct emissions from crop residue decomposition, fertilizer N application, and the fraction of N subject to leaching were considered a function of the ratio of precipitation to potential ET during the growing season at the experimental site. EFs were adopted from several northern China–specific studies (47–49), and _ENREF_1$EF_{RES} = 0.0059 \times$ Prc was used to estimate N_2O emissions from crop residue decomposition (here, Prc represents annual precipitation). The fraction of inorganic N fertilizer that volatilized as NH_3- and NO_x-N ($FRAC_{GASF}$) was assumed to be 16% for wheat and pea, and 21% for maize and the fraction of inorganic N fertilizer and crop straw N associated with nitrate leaching ($FRAC_{LEACH}$) was estimated to be 14, 14, and 19% for wheat, pea, and maize, respectively.

EFs from manufacturing N and P fertilizers, pesticides, and plastic film were obtained from the Chinese Core Life Cycle Database (50). Emissions associated with irrigation were based on the consumption of diesel fuel and electricity for pumping irrigation water from underground. The more irrigation that is used, the more fuel/electricity that is consumed to pump water. Based on several studies conducted in the arid and semiarid northern

Table 3. N fixation of relay-planted pea and monoculture pea

Effect	Grain yield ($kg \cdot ha^{-1}$)		Pea N ($kg\ N \cdot ha^{-1}$)					Maize N ($kg\ N \cdot ha^{-1}$) in		
	Pea	Maize	Seed	Straw	Total	%Ndfa*	Ndfa† ($kg \cdot ha^{-1}$)	Seed	Straw	Total
Year										
2012	4,250	12,749	158.7	116.5	275.1	60.8	173.8	191.5	60.9	252.4
2013	5,136	12,533	160.9	84.1	245	61.0	148.8	168.1	84.7	252.8
2014	4,656	12,577	155.6	106.1	261.7	61.0	150.7	174.6	85.4	259.9
LSD (0.05)	876	1,863	13.6	26.7	31.2	5.4	15.9	25.8	8.1	18.7
Cropping (C)										
Relay	4,915	14,182	166	110.2	276.3	61.8	168.9	188.8	77.4	266.2
Mono	3,977	11,058	124.3	89.4	213.7	58.4	124.5	167.3	76.5	243.9
LSD (0.05)	913	1,437	13.8	27.4	30.2	5.1	16.6	18.1	9.2	12.9
Nitrogen rate (N)										
N0	4,276	11,696	136.9	90.4	227.3	63.7	144.5	144.1	41.4	185.6
N1	5,085	13,544	174.3	119.7	294.0	58.3	171.0	212.0	112.5	324.5
LSD (0.05)	764	1,328	12.1	23.3	25.5	5.2	17.8	20.0	27.3	22.2
Maize density (D)										
D1	5,084	10,947	169.3	132.4	290	59.0	176.4	153.3	73.4	226.7
D2	5,066	12,831	172.3	109.2	281.5	60.5	172.3	178.8	80.9	259.6
D3	4,595	14,083	159.9	97.4	257.3	66.0	158.0	202.1	76.6	278.9
LSD (0.05)	398	1,175	9.7	20.1	20.6	4.8	13.9	16.7	6.9	17.9
Significance										
Year	NS‡	NS	NS	NS	NS	NS	NS	NS	NS	NS
Cropping	0.021	0.009	0.001	0.004	0.002	NS	<0.001	0.000	0.019	0.002
Nitrogen	0.000	0.001	0.011	0.001	0.013	NS	0.009	0.000	<0.001	0.013
Density	0.002	0.041	0.021	0.013	0.029	NS	0.023	0.002	0.041	0.029
C × N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
N × D	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
D × C	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.039

Comparisons between zero (N0) and recommended (N1) N fertilizer rates and relayed maize grown at low (D1), medium (D2), and high (D3) plant densities in 2012, 2013, and 2014.

*N fixed through symbiotic N_2 fixation from the atmosphere.

†Averaged across three years and various treatments, intercropped pea fixed 35.7% more N than sole pea, and pea plants grown with N fertilizer (i.e., N1 treatment) fixed 18.3% more N from the atmosphere than pea plants grown in the no-N fertilizer (N0) treatment. In the pea–maize intercropping systems, nutrient sharing occurred between the intercropped pea and intercropped maize during the cogrowth period, where intercropped maize plants require more N to optimize growth, which may have forced intercropped pea plants to fix more N from the atmosphere. Also, N fertilizer applied to the system may have stimulated root growth of intercropped pea plants more than sole pea; the increased root growth in the N1 treatment, in turn, promoted nodulation and thus fixed more N from the atmosphere.

‡NS, not significant at $P \leq 0.05$.

China and the Chinese Core Life Cycle Database (43, 47, 48), an average EF of 0.7594 $CO_2eq \cdot mm^{-1}$ of irrigation was used in the emission estimate associated with irrigation.

The N_2O EF for crop straw N is usually low; in arid and semiarid areas, emission differences are small or negligible among crops such as barley (*Hordeum vulgare* L.), field pea, wheat, and canola (*Brassica napus* L.). Thus, the coefficients defined in the 2013 IPCC guidelines as default EFs for crop straw were used in the emission estimate (24).

The boundaries were set from the manufacture and transportation of crop inputs (e.g., fertilizers and pesticides) to the farm gate and then from the application of crop inputs in the field to crop harvest (*SI Appendix*, Fig. S6). Estimated within the set boundaries, emissions included those from energy use and N_2O emissions from nonenergy sources, whereby N_2O and CH_4 emissions were converted to CO_2eq. The estimated carbon footprint was based on the global warming potential (GWP) in a time horizon of 100 y ($GWPN_2O = 298$ CO_2eq) by converting N_2O to CO_2eq as defined in the IPCC guidelines (24).

The estimated carbon footprint of each cropping system was assessed from three metrics: 1) emission footprint per unit of grain produced ($kg\ CO_2eq \cdot t^{-1}$ grain), 2) emission footprint per unit of straw biomass ($kg\ CO_2eq \cdot t^{-1}$ biomass), and 3) emission footprint per unit of net return from crop production ($kg\ CO_2eq \cdot US\$100^{-1}$ net return).

Root Barrier Treatments and Root Measurements. One of the key hypotheses was that some level of belowground interspecies interaction occurs in relay-planting systems, which could lead to increased root growth (root biomass) and nutrient sharing in the rhizosphere between relay crops. To test this hypothesis, we designed three root barrier treatments, implemented in 2007 to 2009 and again in 2014 to 2016: 1) a solid plastic sheet physically inserted between the two relay strips in the 0- to 110-cm rooting zone in each plot; the solid plastic does not allow sharing of soil resources between the two strips (no-sharing treatment); 2) a nylon mesh barrier (with aperture of 100 μm) physically inserted between the strips along the 0- to 110-cm rooting zone in each plot; the mesh allows water and nutrients to move freely between strips, but no physical penetration or overlaying of roots between strips (partial-sharing treatment); and 3) no root barrier inserted between the strips (full-sharing treatment). The full-sharing treatment allows water and nutrients to be exchanged freely and the roots of the relayed crops to penetrate into neighboring strips.

Detailed measurements of soil water in various soil layers were made in all 6 y for the different crop strips. In 2014, 2015, and 2016, roots were sampled three times at wheat flowering, maize tasseling, and maize grain-filling each year. At each sampling time, roots were sampled using a monolith method in four steps: 1) Prepare sampling trenches: A trench (100 cm long × 60 cm wide × 120 cm deep) was manually created in each plot, with the trench length perpendicular to the crop row. Each trench covered three rows of wheat and one row of maize in relay planting and six rows of wheat or two rows of maize in monoculture. The trench provided enough space for the sampler to work directly within the root–soil matrix; 2) Mark the monoliths: The surface of the root–soil profile was smoothed by hand, and the sampling area was marked using a colored marker. The root–soil monolith was 40 cm long × 20 cm wide × 20 cm deep for each of the two intercrops and 80 cm

https://doi.org/10.1073/pnas.2106382118

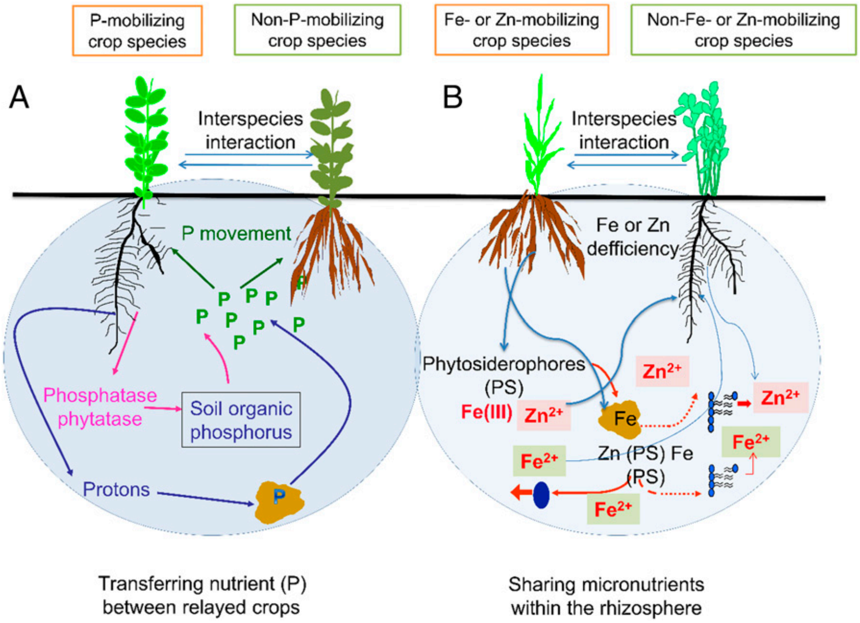

Fig. 7. Potential nutrient mobilization and sharing within the rhizospheres of relayed crops. (*A*) P as an example to illustrate possible interspecific facilitation for nutrient sharing between nutrient-mobilizing and non-nutrient-mobilizing crop species in relay systems, and (*B*) two essential micronutrients—iron (Fe) and zinc (Zn)—as examples to illustrate possible nutrient enhancement through belowground interspecies interactions when two crops with contrasting growth habits are relay planted in field strips (adapted from ref. 21 with modifications).

long × 20 cm wide × 20 deep for monoculture crops. The marking system allowed the five monoliths to be sampled in each root–soil profile. For relay planting, five monoliths were marked in both relayed wheat and relayed maize; 3) Remove the monoliths: From the top layer of the profile, each monolith was cut following the marked lines using a sharp knife. A metal sheet with a sharpened end was horizontally inserted into the profile 40 cm deep to remove the entire monolith. Each root–soil monolith was placed in a 0.2-mm mesh bag, soaked in water for 1 h, gently stirred, and hand-scrubbed to clean the soil. The remaining debris was removed from the roots by hand. In the full-sharing treatment, some monoliths contained wheat and maize roots, which were distinguished by their visual appearance; and 4) Determine root parameters: Root length and surface area were immediately measured using an EPSON scanner in conjunction with Win-RHIZO image analysis (Régent Instruments Inc.). The roots were oven-dried for 30 min at 105 °C to deactivate enzymes and then at 80 °C until constant mass before weighing for root biomass. Root weight density (grams root dry weight per cubic centimeter), root length density (centimeter root length per cubic centimeter), and root surface area density (square centimeters of root surface area per cubic centimeter) were calculated from the soil volume of the monolith. With the relay systems, each crop had a soil volume of 16,000 cm^3, totaling 32,000 cm^3 as per the monoculture crops.

Land Equivalent Ratio. Land equivalent ratio (LER) is the land area required by sole crops to produce the same volume of grain yield as that in the relay-planting system. An LER > 1.0 indicates a yield advantage of relay-planted crops over monoculture crops, with the reverse being true for an LER < 1.0. The ratio was calculated using the following equation (17, 30):

$$\mathrm{LER} = \frac{(\mathrm{LER}_{\mathrm{cool}} + \mathrm{LER}_{\mathrm{warm}})}{2} = \left[\left(\frac{Y_{\mathrm{rel-cool}}}{Y_{\mathrm{mono-cool}}} + \frac{Y_{\mathrm{rel-warm}}}{Y_{\mathrm{mono-warm}}}\right)\Big/2\right] \times 100, \quad [4]$$

where $Y_{\mathrm{rel-cool}}$ and $Y_{\mathrm{rel-warm}}$ are the yield of relayed cool- and warm-season crops, respectively, $Y_{\mathrm{mono-cool}}$ and $Y_{\mathrm{mono-warm}}$ are the yield of the corresponding cool- and warm-season monoculture crops, respectively, and

Table 4. A compensatory effect on soil water between pea and maize in the relay system

Growing stage	Water availability*	Root barrier treatment† Full-sharing	No-sharing	Difference
		mm		
During pea/maize cogrowth period	Deficit	30.4 a‡	8.2 a	22.2 ab
	Suboptimal	28.8 a	4.3 b	24.5 a
	Optimal	24.7 b	4.4 b	20.3 b
Postharvest relay-planted pea	Deficit	5.3 a	−33.7 a	39.1 a
	Suboptimal	2.5 b	−34.1 a	36.7 ab
	Optimal	1.4 b	−31.3 a	32.7 b

*The test was conducted at three levels of water availability that were implemented through irrigation amounts (*SI Appendix*, Table S1).
†Defined in the footnote of Table 2.
‡Different letters in the same column in each section denote significant differences at $P \leq 0.05$. An important feature of relay planting, when incorporated in the system integration model, is the coordination of resource use between relayed crops, providing a compensatory effect to the warm-season maize after the cool-season pea or wheat is harvested. At this time, relayed maize grows vigorously, using accessible resources in both strips, leading to a compensatory effect in soil water use.

LER_{cool} and LER_{warm} are the LER of the relayed cool- and warm-season crops, respectively.

Belowground Interspecies Interaction. For grain yield, biomass, and root traits in the three root barrier treatments, we developed three equations (Eqs. 5–7) to compare the following: 1) full-sharing and no-sharing treatments to determine the contribution of belowground interspecific interactions to increased productivity (yield, biomass, and root dry weight); 2) full-sharing and partial-sharing treatments to determine the effect of root overlapping on the two relayed crops; and 3) partial-sharing and no-sharing treatments to determine the effect of water and nutrient exchange between the relayed strips:

$$\text{Belowground interaction}\,(\%) = \frac{Y_{\text{Full}} - Y_{\text{No}}}{Y_{\text{No}}} \times 100 \qquad [5]$$

$$\text{Root overlaying effect}\,(\%) = \frac{Y_{\text{Full}} - Y_{\text{Partial}}}{Y_{\text{Partial}}} \times 100 \qquad [6]$$

$$\text{Exchange}\,\,(\%) = \frac{Y_{\text{Partial}} - Y_{\text{No}}}{Y_{\text{No}}} \times 100, \qquad [7]$$

where Y_{Full}, $Y_{Partial}$, and Y_{No} are productivity (grain yield, biomass, and root dry weight) of the relay-planted crops grown in the full-sharing, partial-sharing, and no-sharing treatments, respectively.

We also developed an equation (Eq. **8**) to quantify the relative contribution of belowground interspecies interactions to increased productivity of the relayed crops compared to the corresponding monoculture crops:

$$\text{Relative contribution}\,\,(\%) = \frac{\Delta x_{\text{Full}} - \Delta x_{\text{No}}}{\Delta x_{\text{No}}} \times 100, \qquad [8]$$

where Δx is the yield advantage of relay planting over monoculture (i.e., difference in yield between relay planting and corresponding monoculture), and the "Full" and "No" subscripts denote the full-sharing and no-sharing treatments, respectively.

Other root traits, including root length density, root surface area density, and root tips, were also measured, and the treatment effects for these variables were generally similar to those for root dry weight. Some of the treatment effects for root traits have been published elsewhere (29). Here, we report root dry weight as a representative belowground variable.

Estimate of N_2 Fixation by Pea. Nitrogen fixed by pea plants from the atmosphere was estimated using the natural abundance method (51), where the percent N derived from the atmosphere ($\%N_{dfa}$) in the total aboveground plant N was estimated as the following:

$$\%N_{\text{dfa}} = 100 \times \frac{\delta^{15}N_{\text{ref}} - \delta^{15}N_{\text{pea}}}{\delta^{15}N_{\text{ref}} - b}, \qquad [9]$$

where $\delta^{15}N_{ref}$ and $\delta^{15}N_{pea}$ are the δ^{15}N(‰) values of a nonlegume reference crop (an early-maturing spring maize in the study) and pea, respectively, both grown at the same field in the testing years. The b value (–1.05) was derived from $\delta^{15}{}_N$ natural abundance analysis of pea plants grown under N-free sand media (51).

The quantity of N ($kg \cdot ha^{-1}$) fixed by pea plants from the atmosphere (N_{dfa}) was the product of $\%N_{dfa}$ times aboveground plant dry mass times N concentration.

Compensatory Effect. We hypothesized that relaying the cool- and warm-season crops creates compensatory effects. The earlier-maturing, cool-season crop is harvested nearly 2 mo earlier than the warm-season crop. Thus, maize will receive a temporal compensatory effect from the cool-season crop strip after the cool-season crop is harvested. To quantify the compensatory effect, we determined the relative PGR ($kg \cdot ha^{-1} \cdot d^{-1}$) of relayed maize relative to monoculture maize as follows:

$$\text{PGR} = \frac{W_2 - W_1}{t_2 - t_1}, \qquad [10]$$

where w_1 and w_2 are maize plant or root biomass ($kg \cdot ha^{-1}$) measured on two consecutive dates, t_1 and t_2, respectively.

The compensatory effect was determined as the difference in root growth rate between relayed maize and corresponding monoculture maize as the following:

$$C_{\text{effect}} = \text{RGR}_{\text{rel}}/\text{RGR}_{\text{Mono}}, \qquad [11]$$

where RGR_{rel} is the plant (or root) growth rate of relayed maize and RGR_{mono} is the plant (or root) growth rate of monoculture maize.

Interspecies Competitiveness and Aggressiveness. We also hypothesized that during the cogrowth period, the two relayed crops would compete for soil water and nutrients. To quantify competitiveness, we created two terms: competitiveness (Cr) and aggressiveness (Ar), and the magnitude of the interactions was quantified as follows:

$$Cr = \left[\left(\frac{Y_{\text{rel-cool}}/Y_{\text{mono-cool}}}{Y_{\text{rel-warm}}/Y_{\text{mono-warm}}}\right) \times \frac{Pr_{\text{warm}}}{Pr_{\text{cool}}}\right] - \left[\left(\frac{Y_{\text{rel-warm}}/Y_{\text{mono-warm}}}{Y_{\text{rel-cool}}/Y_{\text{mono-cool}}}\right) \times \frac{Pr_{\text{cool}}}{Pr_{\text{warm}}}\right], \qquad [12]$$

where $Y_{rel-cool}$ and $Y_{mono-cool}$ are the productivity of the cool-season relayed crop and monoculture, respectively, $Y_{rel-warm}$ and $Y_{mono-warm}$ are the productivity of the warm-season relayed crop and monoculture, respectively, and Pr_{warm} and Pr_{cool} are the proportion of area occupied by the warm- and cool-season crops in the relay system, respectively. Using pea + maize relay planting as an example, a positive Cr value indicates that the cool-season relayed crop dominates the warm-season relayed crop at a given growth stage, while a value of zero for Cr indicates that both crops are equally competitive.

Aggressiveness measures the relative competitiveness of one relayed crop over the other and was determined as follows:

$$Ar_{\text{cool}} = \left(\frac{Y_{\text{rel-cool}}}{Y_{\text{mono-cool}} \times Pr_{\text{cool}}}\right) - \left(\frac{Y_{\text{rel-warm}}}{Y_{\text{mono-warm}} \times Pr_{\text{warm}}}\right) \qquad [13]$$

$$Ar_{\text{warm}} = \left(\frac{Y_{\text{rel-warm}}}{Y_{\text{mono-warm}} \times Pr_{\text{warm}}}\right) - \left(\frac{Y_{\text{rel-cool}}}{Y_{\text{mono-cool}} \times Pr_{\text{cool}}}\right). \qquad [14]$$

A value of zero for Ar indicates that both crops are equally competitive, while a positive Ar value indicates that the specified relayed crop has a competitive advantage over the other relayed crop.

Statistical Analysis. All variables, including each crop input, output (yield, biomass, root-related traits, and net return), and estimated greenhouse gas emissions and resultant carbon footprints for each treatment across the 12 study years, were combined into a single dataset. The scale, size, and scope of the experiments varied slightly among years. Therefore, the dataset was analyzed using the principle of the subgrouping effect of meta-analysis (23) to generate comprehensive results: 1) treatment effects were assessed in the same or different subgroups, even if the "effect size" differed or treatment subgroups appeared in different study years (23); 2) the Q-statistic was used to test the null hypothesis that all the 16 experiments shared a common effect size; 3) the i^2 statistic was used to quantify the proportion of observed variance that reflected differences in true effect sizes (i.e., heterogeneity); and 4) Tau^2 was used to represent the variance of true effect sizes. Following the principle of the subgrouping effect, differences among treatments were assessed with the Tukey–Kramer test at $P \leq 0.05$ using a mixed model (52). Additionally, linear and nonlinear regression analyses were performed to determine the relationships between the response variables (crop yield, biomass, net return, and emission footprint) and independent variables (ET, irrigation amount, and N fertilizer rate).

Data Availability. All study data are included in the article and/or *SI Appendix*.

ACKNOWLEDGMENTS. We are grateful to Dr. Chris Barrett (Cornell University), Dr. Ken Giller (Wageningen Centre for Agroecology and Systems Analysis, The Netherlands), and Dr. John Kirkegaard (The Commonwealth Scientific and Industrial Research Organisation, Australia), for their suggestions of improving the manuscript. The work was supported by the Research Program Sponsorship of Gansu Provincial Key Laboratory of Aridland Crop Science, Gansu Agricultural University (Grant GSCS–2016–01), the Innovation Group of Basic Research in Gansu Province (Grant 20JR5RA037), the National Natural Science Foundation of China (Grants 31360323 and 31771738), and the Modern Agro-Industry Technology Research System (Grant CARS–22–G–12). Additional funds to the field experiments were provided by the National Key Technology Research and Development Program (Grant 2012BAD14B10), the Special Fund for Agro-Scientific Research in the Public Interest (Grant 201103001), and the Excellent Youth Foundation of Gansu Scientific Committee (Grant 1111RJDA006). In each of the 12 study years, 10 to 30 undergraduate and graduate students from Gansu Agricultural University were involved in plot implementation and data collection during their thesis training at the Wuwei Research and Education Station. Drs. Wen Yin and Zhilong Fan from the College of Agronomy, Gansu Agricultural University, were involved in supervising some students in experimental implementation and data collection.

1. S. K. Lowder, J. Skoet, T. Raney, The number, size, and distribution of farms, smallholder farms, and family farms worldwide. *World Dev.* **87**, 16–29 (2016).
2. A. A. Golub *et al*., Global climate policy impacts on livestock, land use, livelihoods, and food security. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 20894–20899 (2013).
3. K. H. M. Siddique, X. Li, K. Gruber, Rediscovering Asia's forgotten crops to fight chronic and hidden hunger. *Nat. Plants* **7**, 116–122 (2021).
4. G. S. Cumming *et al*., Implications of agricultural transitions and urbanization for ecosystem services. *Nature* **515**, 50–57 (2014).
5. K. C. Seto, N. Ramankutty, Hidden linkages between urbanization and food systems. *Science* **352**, 943–945 (2016).
6. M. Herrero *et al*., Smart investments in sustainable food production: Revisiting mixed crop-livestock systems. *Science* **327**, 822–825 (2010).
7. J. Poore, T. Nemecek, Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992 (2018).
8. X. Zhang *et al*., Managing nitrogen for sustainable development. *Nature* **528**, 51–59 (2015).
9. X. Chen *et al*., Producing more grain with lower environmental costs. *Nature* **514**, 486–489 (2014).
10. Z. Cui *et al*., Pursuing sustainable productivity with millions of smallholder farmers. *Nature* **555**, 363–366 (2018).
11. Z. Qu, J. Wang, T. Almøy, L. R. Bakken, Excessive use of nitrogen in Chinese agriculture results in high N(2) O/(N(2) O+N(2)) product ratio of denitrification, primarily due to acidification of the soils. *Glob. Change Biol.* **20**, 1685–1698 (2014).
12. J. H. Guo *et al*., Significant acidification in major Chinese croplands. *Science* **327**, 1008–1010 (2010).
13. R. Chen, A. de Sherbinin, C. Ye, G. Shi, China's soil pollution: Farms on the frontline. *Science* **344**, 691 (2014).
14. H. C. J. Godfray, Ecology. Food and biodiversity. *Science* **333**, 1231–1232 (2011).
15. W. Zhang *et al*., Closing yield gaps in China by empowering smallholder farmers. *Nature* **537**, 671–674 (2016).
16. N. D. Mueller *et al*., Closing yield gaps through nutrient and water management. *Nature* **490**, 254–257 (2012).
17. F. Hu *et al*., Boosting system productivity through the improved coordination of interspecific competition in maize/pea strip intercropping. *Field Crops Res.* **198**, 50–60 (2016).
18. E. Betencourt, M. Duputel, B. Colomb, D. Desclaux, P. Hinsinger, Intercropping promotes the ability of durum wheat and chickpea to increase rhizosphere phosphorus availability in a low P soil. *Soil Biol. Biochem.* **46**, 181–190 (2012).
19. Z. G. Wang *et al*., Intercropping maintains soil fertility in terms of chemical properties and enzyme activities on a timescale of one decade. *Plant Soil* **391**, 265–282 (2015).
20. W. F. Cong *et al*., Intercropping enhances soil carbon and nitrogen. *Glob. Change Biol.* **21**, 1715–1726 (2015).
21. L. Li, D. Tilman, H. Lambers, F. S. Zhang, Plant diversity and overyielding: Insights from belowground facilitation of intercropping in agriculture. *New Phytol.* **203**, 63–69 (2014).
22. Y. Gan *et al*., Ridge-furrow mulching systems—An innovative technique for boosting crop productivity in semiarid rain-fed environments. *Adv. Agron.* **118**, 429–476 (2013).
23. M. Borenstein, J. P. T. Higgins, Meta-analysis and subgroups. *Prev. Sci.* **14**, 134–143 (2013).
24. G. Myhre *et al*., "Anthropogenic and natural radiative forcing" in *Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, F. Stocker *et al*., Eds. (Cambridge University Press, Cambridge, 2013), vol. T, pp. 659–740.
25. F. Gou *et al*., On yield gaps and yield gains in intercropping: Opportunities for increasing grain production in northwest China. *Agric. Syst.* **151**, 96–105 (2017).
26. C. J. Li *et al*., Crop nitrogen use and soil mineral nitrogen accumulation under different crop combinations and patterns of strip intercropping in northwest China. *Plant Soil* **342**, 221–231 (2011).
27. Q. Chai *et al*., Regulated deficit irrigation for crop production under drought stress. A review. *Agron. Sustain. Dev.* **36**, 1–21 (2016).
28. J. Wu *et al*., Ridge-furrow cropping of maize reduces soil carbon emissions and enhances carbon use efficiency. *Agric. Ecosyst. Environ.* **256**, 153–162 (2018).
29. Y. Wang *et al*., Interspecies interactions in relation to root distribution across the rooting profile in wheat-maize intercropping under different plant densities. *Front Plant Sci* **9**, 483 (2018).
30. G. Chen *et al*., Enhancing the systems productivity and water use efficiency through coordinated soil water sharing and compensation in strip-intercropping. *Sci. Rep.* **8**, 10494 (2018).
31. Q. Chai *et al*., Water-saving innovations in Chinese agriculture. *Adv. Agron.* **126**, 149–201 (2014).
32. C. Huang *et al*., Economic performance and sustainability of a novel intercropping system on the North China Plain. *PLoS One* **10**, e0135518 (2015).
33. Y. Xu, J. Li, S. Jiao, Impacts of Chinese urbanization on farmers' social networks: Evidence from the urbanization led by farmland requisition in Shanghai. *J. Urban Plann. Dev.* **142**, e05015008 (2016).
34. N. K. Sharma *et al*., Increasing farmer's income and reducing soil erosion using intercropping in rainfed maize-wheat rotation of Himalaya, India. *Agric. Ecosyst. Environ.* **247**, 43–53 (2017).
35. V. K. Choudhary, P. S. Kumar, Productivity, water use and energy profitability of staggered maize–legume intercropping in the eastern Himalayan Region of India. *Proc. Natl. Acad. Sci. Ind. B.S.* **86**, 547–557 (2016).
36. M. O. Martin-Guay, A. Paquette, J. Dupras, D. Rivest, The new Green Revolution: Sustainable intensification of agriculture by intercropping. *Sci. Total Environ.* **615**, 767–772 (2018).
37. S. Keesstra *et al*., The superior effect of nature based solutions in land management for enhancing ecosystem services. *Sci. Total Environ.* **610–611**, 997–1009 (2018).
38. S. Suweis, J. A. Carr, A. Maritan, A. Rinaldo, P. D'Odorico, Resilience and reactivity of global food security. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 6902–6907 (2015).
39. M. C. Nelson *et al*., Climate challenges, vulnerabilities, and food security. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 298–303 (2016).
40. J. W. McArthur, J. D. Sachs, Agriculture, aid, and economic growth in Africa. *World Bank Econ. Rev.* **33**, 1–20 (2019).
41. I. O. Olanipekun, G. O. Olasehinde-Williams, R. O. Alao, Agriculture and environmental degradation in Africa: The role of income. *Sci. Total Environ.* **692**, 60–67 (2019).
42. W. Schröder, S. Nickel, Spatial structures of heavy metals and nitrogen accumulation in moss specimens sampled between 1990 and 2015 throughout Germany. *Environ. Sci. Eur.* **31**, 33 (2019).
43. Anonymous,*China Yearbook of Agricultural Price Survey* (China Statistics Press, Hong Kong, 2017).
44. P. Rochette *et al*., Soil nitrous oxide emissions from agricultural soils in Canada: Exploring relationships with soil, crop and climatic variables. *Agric. Ecosyst. Environ.* **254**, 69–81 (2018).
45. Y. Gan *et al*., Improving farming practices reduces the carbon footprint of spring wheat production. *Nat. Commun.* **5**, 5012 (2014).
46. A. Charles *et al*., Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis. *Agric. Ecosyst. Environ.* **236**, 88–98 (2017).
47. Y. Y. Wang *et al*., Concentration profiles of CH4, CO2 and N2O in soils of a wheat-maize rotation ecosystem in North China Plain, measured weekly over a whole year. *Agric. Ecosyst. Environ.* **164**, 260–272 (2013).
48. Y. Lu, Y. Huang, J. Zou, X. Zheng, An inventory of N(2)O emissions from agriculture in China using precipitation-rectified emission factor and background emission. *Chemosphere* **65**, 1915–1924 (2006).
49. X. T. Ju *et al*., Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 3041–3046 (2009).
50. Anonymous, *Chinese Life Cycle Database (CLCD)* (World Research Institute, Geneva, Switzerland, 2018).
51. G. Shearer, D. H. Kohl, N2-fixation in field settings: Estimations based on natural 15N abundance. *Aust. J. Plant Physiol.* **13**, 699–756 (1987).
52. R. C. Littell, G. A. Milliken, W. W. Stroup, R. D. Wolfinger, *SAS System for Mixed Models* (SAS Institute Inc., Cary, NC, ed. 2, 2006).