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## Research Article

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# Expanding low-input summer soybean in China's winter wheat belt: climate, water and food trade-offs

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## Abstract

Where cropland is no longer expanding, few measures jointly reduce fertilizer N, reactive N losses, and irrigation withdrawal. A legume in the summer slot of an existing rotation is one of them. For China, importing about 85% of its soybean, it is also a route to domestic supply. But when unfertilized soybean replaces maize, a season of fertilizer and irrigation is withdrawn with it. In field trials and existing model assessments the two effects are inseparable by design. Addition and substitution act on different land uses, so their outcomes cannot be inferred from one another. Here we simulate soil carbon, nitrogen, food, and water from 2020 to 2100 with gridded LPJ-GUESS over 5035 cells of eastern China's winter wheat

belt. DSSAT and APSIM run at shared stations, under four climate models and three emission scenarios. Unfertilized, unirrigated summer soybean enters by fallow-window addition or by substitution for summer maize, each paired with a control keeping the existing system. Effects are attributed by withdrawing crop, N fertilizer, and irrigation one at a time. Nearly all the substitution pathway's climate benefit, 3.0 Mg CO<sub>2</sub>e per hectare per year, comes from the withdrawn fertilizer N. Switching to the legume itself contributes close to zero; its role is to keep the zero-N system viable. Addition raises grain yield by 38% and improves soil carbon and N losses, at a 13–45 mm per year decline in the net groundwater balance. Substitution saves irrigation and raises recharge, gaining 65–85 mm per year, at a 47% grain loss. The lever is the nitrogen locked into the summer slot. Recharge costs are attenuated in the vadose zone and cannot be metered; abstraction savings can. Within the overdraft belt soybean should enter by substitution; this difference in meterability gives a basis for subsidies differentiated by pathway and zone.

Keywords: cropping-system conversion; low-input summer soybean; biological N fixation; soil organic carbon; groundwater; nitrous oxide

## 1 Introduction

Legume crops sustain yield without added N through symbiotic N fixation, making them one of the few crops that can cut N without cutting yield. But introducing one into a rotation always displaces some existing land use, so its effect depends on what it replaces. China's soybean imports amount to roughly 85% of its consumption. This is the highest dependence among the five bulk agricultural commodities listed in the supply–demand balance sheet of the Ministry of Agriculture and Rural Affairs<sup>[1]</sup>. Expanding soybean cultivation is already a national policy priority, and the state has at the same time set emission-reduction targets for agriculture. Both targets converge on the same season of cropland. With cropland no longer expanding and yield growth slowing in the main producing regions, what can chiefly be adjusted is what occupies the summer slot after the winter wheat harvest. Beyond the summer use of this land, taking cropland out of cultivation in exchange for ecological gains is one alternative. Abandoned fields are usually recultivated before they accumulate any substantial net carbon, so their sequestration is limited<sup>[2]</sup>. The emission reductions achievable through cropland management exceed the carbon that abandonment could store<sup>[3]</sup>. Environmental gains must therefore be sought mostly in the management of cropland that remains in cultivation. In the winter wheat belt of eastern China, the summer window is mostly left fallow or planted to summer maize. The choice of summer crop simultaneously determines

the N application rate, the amount of groundwater withdrawn for irrigation, and the quantity of crop residue returned to the soil. Rates are 264 kg N per hectare on winter wheat and 204 on summer maize, from farm surveys across the North China Plain (NCP)<sup>[4]</sup>. The first two of these are precisely this region's binding constraints. Cumulative groundwater depletion in the NCP has reached 160 km<sup>3</sup><sup>[5][6]</sup>. Of the simulation domain, 27.7% has been designated part of the groundwater-overdraft belt and placed under abstraction control<sup>[7][8]</sup>. Well irrigation cannot be sustained indefinitely<sup>[9]</sup>. The reactive-N losses of this high-input system are already empirically documented<sup>[10]</sup>. The soybean gap and the water and nitrogen constraints thus converge here: producing more soybean on one side, applying less N and pumping less water on the other. Both point to the same action: growing one season of unfertilized, unirrigated summer soybean in the post-wheat window. Sustaining yields at lower input levels has long had precedent in China<sup>[11]</sup>.

Introducing legumes into rotations to reduce N input and losses is well supported at the field scale. A legume preceding crop lowers the fertilizer need of the crop that follows<sup>[12][13]</sup>; cover crops generally lower leaching<sup>[14]</sup>. Yet the net contribution of grain legumes to soil N is often insignificant in the field<sup>[15]</sup>. The effect of a legume preceding crop on the crop that follows varies with water supply<sup>[16]</sup>. Adding one season of summer soybean after wheat has a long field record in this region<sup>[17][18]</sup>, and its evaluation falls into two classes. Field trials compare wheat–soybean with wheat–maize, or soybean–wheat with fallow–wheat. In the six-year experiment at Luancheng, rotations containing soybean lowered greenhouse gas emissions and raised protein output<sup>[19]</sup>, and other stations report differences in yield and soil indicators<sup>[20][16]</sup>. Point-scale process models show that replacing summer maize with soybean lowers evapotranspiration and its water footprint, easing groundwater-overdraft pressure<sup>[21]</sup>, and that region-scale substitution rotations can slow water-table decline<sup>[22]</sup>. A model comparison of eight cropping systems ranks optimized winter wheat–summer maize best overall, with none of the soybean-containing systems at the top<sup>[23]</sup>. On the modeling side, process-based legume N fixation entered gridded crop models only recently<sup>[24]</sup>.

These studies leave three things unresolved. First, both classes of work compare two cropping systems. Switching to soybean removes one season of fertilizer and one season of irrigation at the same time. The difference between the systems is therefore attributed to the legume, and the attribution is inseparable by design. Second, they have examined only the pathway that substitutes soybean for summer maize. Under warming, early-maturing summer soybean now meets its heat-unit requirement in the post-wheat window nearly everywhere in the region (Sect. 2.1). Adding a soybean season to the fallow window left by single-cropped

winter wheat is therefore a second pathway. It has no fertilizer or irrigation to withdraw; what it changes is the use of bare summer land. The two pathways introduce the same crop, yet they replace a different land use, remove a different set of inputs, and set different water processes in motion. Their net effects should not be the same. One example is that the difference in annual water use between wheat–soybean and wheat–maize changes sign with year type<sup>[18]</sup>. Third, field trials are confined to single stations and a few years, while the responses of soil carbon and groundwater play out over decades. Point-scale models cannot establish whether the sign holds everywhere in the domain. The carbon, nitrogen, and water accounts of the two pathways have never been evolved together within one coupled process set. Gridded process models can do this, yet none has been applied to post-wheat soybean in this region.

Here we address three questions: from which step of the conversion the benefits of introducing summer soybean arise, and on which resource the cost falls under each pathway. A third question is whether conclusions drawn for one pathway can be extrapolated to the other. We simulate each pathway's control and intervention with LPJ-GUESS to 2100 on 5035 grid cells, checking the direction of change with DSSAT and APSIM at the shared stations. We then attribute the effects by withdrawing the crop, the N fertilization, and the irrigation one by one. The results show that nearly all of the climate benefit comes from the fertilizer N withdrawn along with the switch. The two pathways pay their costs in different resources: addition consumes groundwater recharge, substitution loses grain.

## 2 Methods

### 2.1 Study region, cropping systems, and the two pathways

The simulation domain covers the main winter wheat belt of eastern China, 5035 winter wheat grid cells at 0.1° resolution between 106.7–122.6°E and 29.3–41.3°N<sup>[25]</sup> (Fig. 1). It is centered on the NCP, with the Guanzhong Basin on the western side and the Yangtze–Huai region along the southern margin. The dominant systems in the domain are winter wheat–summer maize double cropping and single-cropped winter wheat, along with some winter wheat–summer soybean double cropping. The delineated groundwater-overdraft belt<sup>[7]</sup> was rasterized onto the 0.1° grid into two approximate sub-regions, inside and outside the belt (Fig. 1a).

The two pathways are defined by each grid cell's current system. Cells under single-cropped winter wheat can add a crop of summer soybean, and cells under winter wheat–

summer maize can substitute summer soybean for the maize. The adoption year is 2020, and simulations run to 2100. Of the 5035 grid cells in the domain, 3775 are feasible for both pathways; the remaining cells' feasibility by pathway is shown in Fig. 1a. Whether summer soybean can mature within the post-wheat window is assessed separately, post hoc. Cells are judged against the heat-unit requirement of early-maturing varieties: base temperature 10 °C, 1400 °C·d from sowing to physiological maturity<sup>[26]</sup>. This is consistent with observed growing periods of summer soybean in the NCP<sup>[27]</sup>. A cell is deemed reliably feasible if the requirement is met in at least eight of ten years. Summer soybean matures stably in the large majority of cells. On the northern edge, north of about 39°N, it matures around mid-September by the end of the century, four to six weeks before the first frost in this region. Sensitivity to higher heat-unit requirements is given in Fig. 1b–d and Supplementary Material Text S24.12.

The three models are additionally run together at seven stations or grid cells to check cross-model consistency. Four are used for the substitution pathway: the three long-term observation stations at Fengqiu, Luancheng, and Yucheng, plus one virtual grid cell in western Henan. Three are used for the addition pathway: two virtual grid cells, Guanzhong and the Fenhe valley, plus the real rainfed double-cropping station at Luoyang, in operation since 2009<sup>[28]</sup>. Coordinates, site types, and variety screening for all seven locations are given in Supplementary Material Text S24.1. At these seven locations, the two point-scale models are driven by the same 12 climate members (4 GCMs × 3 SSPs) as LPJ-GUESS (Sect. 2.3).

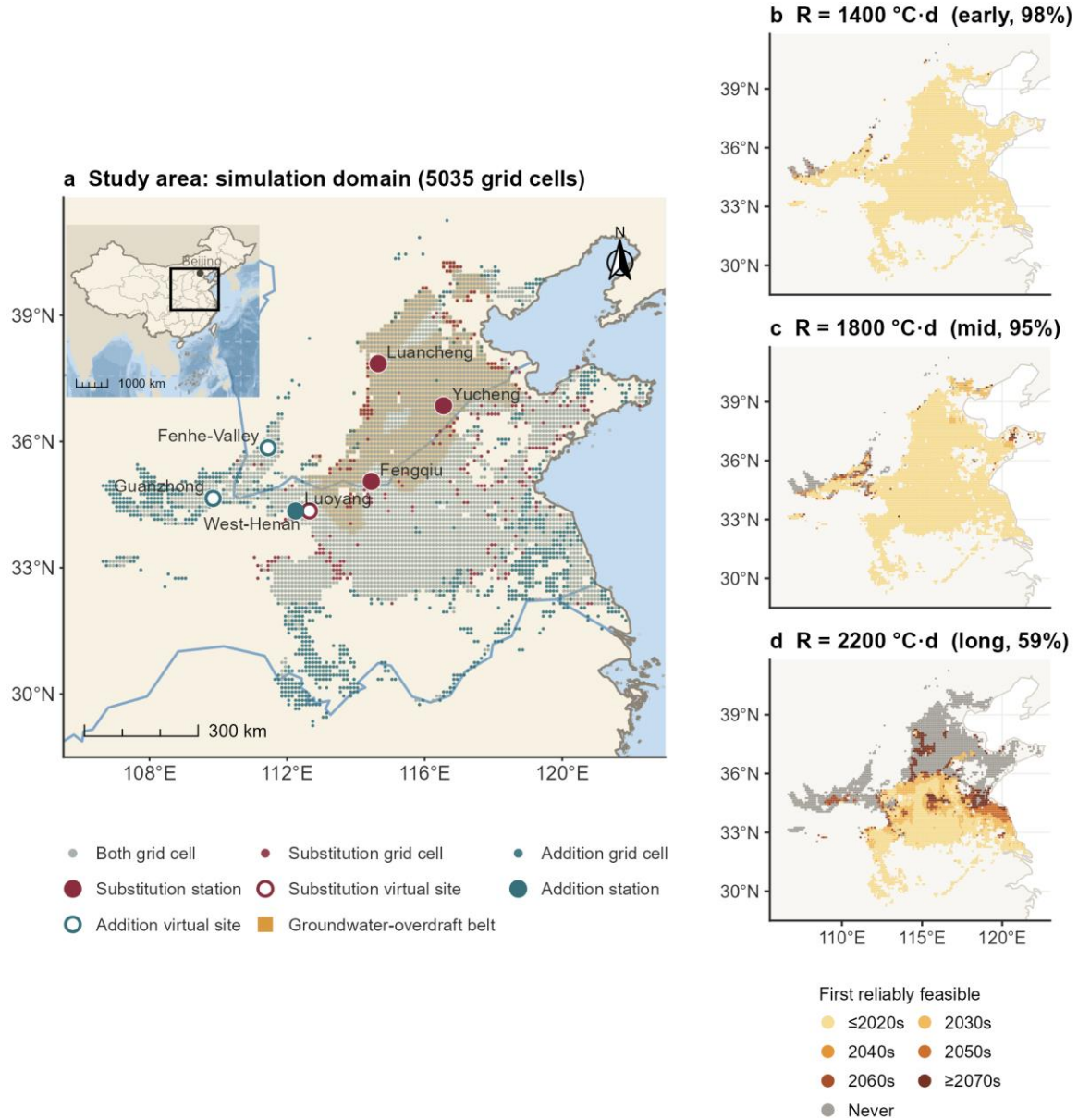


Fig. 1 | Feasibility of the two pathways and of summer soybean maturation. a, The 5035 grid cells coloured by cropping-system domain: both pathways (grey,  $n = 3775$ ), addition only (teal,  $n = 981$ ), substitution only (crimson,  $n = 279$ ). Filled circles, long-term stations run with all three models (substitution: Fengqiu, Luancheng, Yucheng; addition: Luoyang); open circles, virtual grid cells (substitution: western Henan; addition: Guanzhong, Fenhe valley). Pale yellow, the delineated groundwater-overdraft belt (27.7% of the domain). Inset, location within China on the national standard base map. b–d, Decade in which summer soybean first becomes reliably feasible (met in at least 8 of 10 years) in the post-wheat window under heat-unit requirements of 1400 (early-maturing), 1800 (medium-maturing), and 2200  $^{\circ}\text{C}\cdot\text{d}$  (single-season varieties); percentages in the panel titles are shares of cells feasible before 2100; grey, never reliable. Forcing: CMFD 1951–2024 spliced with the reference member (MRI-ESM2-0  $\times$  SSP2-4.5) for 2025–2100. Recomputed with the same criterion for the other 11 climate members, the share of cells reliably feasible before 2100 is 96.5–98.7% across the 12 members for the early-maturing requirement (four-GCM medians 97.1%, 97.6%, and 98.3% under SSP1-2.6, SSP2-4.5, and SSP5-8.5), 91–98% for the medium-maturing requirement, and 48–97% for single-season varieties (four-GCM medians 50%, 74%, and 92%, widening

with emissions); the early-maturing criterion used in this paper is feasible over nearly the whole domain in every member.

## **2.2 Three models and within-year double cropping**

At the regional scale we use LPJ-GUESS 4.0 (revision r10285), with the biological N fixation scheme implemented at that revision by Ma et al.<sup>[24]</sup>. It is run over all 5035 grid cells. Our modifications to that revision include extensions for cropping-system conversion and stand-level output, a correction to one dormancy determination, and data-preparation scripts. These, and the default switch settings, are documented in Supplementary Material Text S24.2.

Both pathways require two crops grown sequentially on the same stand within one year. This is achieved with the double-cropping schedule built into the cropland management scheme<sup>[29]</sup>. The second crop is sown ten days after the harvest–sowing transition date, and the preceding crop is force-harvested ten days before that date. The second crop's heat-unit accumulation window is capped at 150 days, and the two crops share the same stand and soil column. The cropland version of this model has published examples of within-year double cropping<sup>[30]</sup>, and the development of its crop module is described in<sup>[31]</sup>. The transition year is set by a newly added scheduling parameter, after which the original rotation resumes automatically. Scheduling implementation and inter-seasonal N transfer are given in Supplementary Material Text S24.2 and S24.3.

At the site scale we use APSIM Next Generation (source commit 4f4a42fb; PMF crop architecture, the Nutrient module of the CERES lineage, and N fixation via a nodulation module). We also use DSSAT-CSM 4.8.5.000 (CENTURY-type multi-pool soil organic matter, N fixation via the CROPGRO nodulation module). Both models are run at the seven locations listed in Sect. 2.1, with identical sites, forcings, and management settings. Initial soil carbon is set to the 0–30 cm target derived from SoilGrids 2.0. The three models fix nitrogen through different mechanisms: demand-driven in LPJ-GUESS, nodulation modules in the other two. Part of the cross-model spread in N fixation therefore stems from how the process is represented.

## **2.3 Input data and cross-model harmonization**

Forcing and management follow a single alignment protocol across the three models: a common set of climate, soil, N application, and crop-calendar inputs. The point-scale models do not re-fit crop parameters, and the alignment of each input dataset is documented in Supplementary Material Text S24.5–S24.10. Three points bear directly on the interpretation of the results. N application: annual rates are identical across the three models: 264 kg N per

hectare on winter wheat, 204 on summer maize, and 0 on summer soybean. The rates are anchored to a survey of 805 farm households in the NCP<sup>[4]</sup> and applied uniformly across the domain, an extrapolation for the Guanzhong and Yangtze–Huai margins. The historical trajectory is taken from a global, crop-specific reconstruction of synthetic N fertilizer use<sup>[32]</sup>. Plant-available water capacity: the soil physical data derive from the same source, SoilGrids 2.0, but each model converts them in its own way. The resulting plant-available water capacity in LPJ-GUESS exceeds that of the point-scale models by a factor of 1.26–1.88 (median 1.62 across seven stations). This is self-consistent with the higher irrigation amounts in the point-scale models. Climate forcing: the historical segment is taken from the China Meteorological Forcing Dataset v2.0<sup>[33][34]</sup>. The future segment is taken from a China-oriented downscaled CMIP6 product<sup>[35]</sup>. From it we take four global climate models (GCMs; MRI-ESM2-0, MPI-ESM1-2-HR, GFDL-ESM4, CMCC-ESM2) and three emission scenarios (shared socioeconomic pathways, SSPs; SSP1-2.6, SSP2-4.5, SSP5-8.5), 12 climate members in total, with CO<sub>2</sub> concentration following the scenario<sup>[36][37]</sup>. Table 3 and in-text point values use MRI-ESM2-0 × SSP2-4.5 as the reference member; the other members give a range.

## 2.4 Scenario design, climate account, and factor decomposition

Each pathway has a baseline scenario (system unchanged) and an intervention scenario. The two share the entire history before the adoption year and diverge from 2020 (Table 1). Beyond replacing the summer crop, the intervention lowers the N rate on the succeeding winter wheat from 264 to 216 kg N per hectare. This is the mean of farmer practice for wheat after soybean in the same regional survey (216 kg N in wheat–soybean rotations versus 264 in wheat–maize, 73 households)<sup>[4]</sup>. Both pathways share this setting; in the addition pathway it is the sole source of the N application change relative to the control. Summer soybean receives no N fertilizer and no irrigation in any scenario. The main residue retention setting is 25%, with a 90% setting for sensitivity, implemented in all three models. The measured direct return rate of aboveground straw in this region is 55–70%<sup>[38][39]</sup>. The main setting is therefore conservative for the soil carbon gain under addition, and understates the carbon loss under substitution. On the substitution baseline, three further management variants decompose the intervention effect into N fertilization, irrigation, and the crop itself. The variants are summer maize without N fertilizer, without irrigation, and without either (scenarios 5–7, Table 1). Each pathway also has a variant that introduces soybean while keeping wheat at 264 kg N (scenario 8), used to isolate the step of cutting the succeeding wheat's N rate.

The LPJ-GUESS spin-up follows the protocol of its N fixation module paper<sup>[24]</sup>. Potential natural vegetation is established first, and the cropland fraction is ramped from zero to its first historical value at the end of the spin-up. The historical transient segment follows, for a total spin-up length of 3000 years. Initial soil carbon differs across the three models. Incompletely standardized soil treatment has precedent in multi-model comparisons<sup>[40]</sup> (Supplementary Material Text S24.13); the comparison convention is given in Sect. 2.5.

Table 1 | Scenario design and coverage by the three models. The two pathways have different baselines (single-cropped winter wheat for addition; winter wheat–summer maize for substitution), and all relative changes are computed against each pathway's own baseline. Scenarios 5–7 are summer-maize management variants on the substitution baseline. The route from baseline to intervention can be taken in two removal orders (withdraw N fertilizer first and then irrigation, or the reverse). The two orders share the same endpoint. Residue retention is 25% in all scenarios. X indicates that the model was run for that scenario.

| No. | Scenario                                                  | Pathway      | Summer crop    | Summer N        | Summer irrigation | LPJ-GUESS | DSSAT-CSM | APSIM |
|-----|-----------------------------------------------------------|--------------|----------------|-----------------|-------------------|-----------|-----------|-------|
| 1   | Addition baseline                                         | addition     | none           | –               | –                 | X         | X         | X     |
| 2   | Addition intervention                                     | addition     | summer soybean | none            | rainfed           | X         | X         | X     |
| 3   | Substitution baseline                                     | substitution | summer maize   | observed values | observed values   | X         | X         | X     |
| 4   | Substitution intervention                                 | substitution | summer soybean | none            | rainfed           | X         | X         | X     |
| 5   | Substitution baseline, maize unfertilized                 | substitution | summer maize   | none            | observed values   | X         | X         | X     |
| 6   | Substitution baseline, maize unirrigated                  | substitution | summer maize   | observed values | none              | X         | X         | X     |
| 7   | Substitution baseline, maize unfertilized and unirrigated | substitution | summer maize   | none            | none              | X         | X         | X     |

| No. | Scenario                                            | Pathway                    | Summer<br>crop    | Summer N | Summer<br>irrigation | LPJ-<br>GUESS | DSSAT-<br>CSM | APSIM |
|-----|-----------------------------------------------------|----------------------------|-------------------|----------|----------------------|---------------|---------------|-------|
| 8   | Soybean<br>introduced,<br>wheat kept<br>at 264 kg N | addition /<br>substitution | summer<br>soybean | none     | rainfed              | X             | X             | X     |

In a single run, LPJ-GUESS outputs the co-located stands of both pathways. Scenario 8 serves only to isolate the fourth step of the climate account, and is not reported separately for the four dimensions. At the western-Henan station, summer maize is rainfed, so in the point-scale models scenario 6 is identical to scenario 3, and scenario 7 to scenario 5.

The climate account has four terms: upstream fertilizer manufacture, in-field soil nitrous oxide (N<sub>2</sub>O), in-situ soil carbon, and indirect N<sub>2</sub>O from leached N. Upstream fertilizer manufacture is computed as a published emission factor times the scenario N rate, with a central value of 8.3 kg CO<sub>2</sub>e per kg N<sup>[41]</sup>. This factor is the sum of extraction and transport, ammonia synthesis, and product processing and distribution, excluding field emissions. Off-site transformation of leached N is converted with the indirect emission factor of the IPCC 2019 Refinement (EF<sub>5</sub> = 0.011), with leached N taken from model output. In-situ soil carbon is the simulated stock change, annualized over 80 years. Absolute in-field soil N<sub>2</sub>O diverges across process-based models<sup>[42]</sup>. We take its change relative to the control, scaled to an absolute amount against an inventory baseline. The inventory baseline is baseline N application × crop-season emission factor<sup>[43]</sup>, plus baseline residue N × residue emission factor. Nitrous oxide is converted to CO<sub>2</sub>-equivalents using the IPCC AR6 100-year global warming potential of 273, with positive values denoting accounted emissions reduced relative to the control:

$$\Delta C = -[\Delta N_{\text{mfg}} EF_{\text{mfg}} + \beta \Delta N_2 O_{\text{soil}}^{\text{mod}} \frac{44}{28} \text{GWP} + \Delta N_{\text{leach}} EF_5 \frac{44}{28} \text{GWP}] + \frac{\Delta \text{SOC}}{T} \frac{44}{12} \quad (1)$$

Here  $\Delta C$  is the paired net change in the climate account (Mg CO<sub>2</sub>e per hectare per year);  $\Delta$  denotes intervention minus control;  $\Delta N_{\text{mfg}}$  is the change in N application;  $\Delta N_{\text{leach}}$  the change in leached N; EF the respective emission factors;  $\Delta N_2 O_{\text{soil}}^{\text{mod}}$  the modeled change in in-field soil N<sub>2</sub>O;  $\beta = (N_{\text{baseline}} EF_1 + N_{\text{residue, baseline}} EF_{\text{res}}) / N_2 O_{\text{soil, baseline}}^{\text{mod}}$  the coefficient that anchors the model magnitude to the inventory baseline; T the 80-year horizon; GWP the 100-year global warming potential (273); SOC soil organic carbon; and 44/28 and 44/12 the molar-mass conversions. The account attributes emissions within field boundaries and excludes the consequences abroad of fertilizer demand reallocated through markets. The CO<sub>2</sub>

released by urea hydrolysis is carried separately as a supplementary term. The values and sources of all emission factors are given in Supplementary Material Text S24.15.

Because the intervention changes crop, N fertilization, and irrigation at once, we remove items stepwise from the baseline: withdraw summer-crop N, withdraw summer-crop irrigation, then switch crop. We list the cut in the succeeding wheat's N rate as a fourth step, isolated as the difference between scenario 8 and the main intervention. The N-removal and irrigation-removal steps are each run in both orders, forward and reverse, and averaged symmetrically. The crop switch and the succeeding-wheat N cut each have a single order, and are taken as endpoint differences:

$$s_k = \frac{1}{2}(\Delta C_k^{\text{fwd}} + \Delta C_k^{\text{rev}}), \sum_k s_k = \Delta C \quad (2)$$

The steps sum exactly to the total effect. The N-removal and irrigation-removal steps interact: withdrawing N shrinks the crop and lowers its water use. Each step's contribution is therefore a marginal value along the removal path, averaged over the two orders, forward and reverse.

## 2.5 Reporting conventions for each quantity

The three models disagree in the direction of their absolute yield biases over this region. Their absolute soil N<sub>2</sub>O magnitudes also differ by an order of magnitude (station-by-station comparisons in the validation matrix of the Supplementary Material). The comparable quantity in this study is therefore the change relative to each model's own control. For any quantity X,  $\Delta X\% = (X_{\text{intervention}} - X_{\text{control}})/X_{\text{control}} \times 100$ , with intervention and control run at the same grid cell under the same climate member. Regional quantities are weighted by cropland-area share. If the two scenarios share a multiplicative bias, subtraction cancels it exactly (Supplementary Material Text S6). Station-by-station diagnostics show the bias is not purely multiplicative. The usability of relative change is therefore judged empirically, from the three models' convergence and agreement in sign at the shared stations (Table 2). Cross-model consistency is assessed only at the seven shared stations. Domain-scale and grid-cell results are reported primarily from LPJ-GUESS, with the two point-scale models checking the direction at the shared stations. The three models share their inputs (Sect. 2.3), so their agreement reflects structural convergence. Model–observation comparisons cover 2020–2024 (adoption year to the end of the historical forcing; N<sub>2</sub>O uses the 2020–2029 mean), whereas domain-scale headline quantities are taken from 2091–2100. Which model carries each

quantity, and whether it is reported numerically or by direction, is fixed by Table 2; the four dimensions are not commensurable.

Table 2 | Primary reporting model and evidence grading for each compared quantity.

| Quantity                         | Primary reporting                             | Reporting status                                                                                                                       | Basis                                                                                                                                                                                     |
|----------------------------------|-----------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Grain dry matter                 | LPJ-GUESS, domain scale                       | Relative changes reported numerically; direction checked across the three models                                                       | All three models agree in sign; absolute biases known (winter wheat 30–43% low, summer maize 10–30% high)                                                                                 |
| Grain crude protein              | Fixed dry-basis composition × LPJ-GUESS yield | Addition: same sign as dry matter; substitution: reference member +3.3%, sign reversing with emission scenario (Sect. 3.1)             | No bias cancellation in cross-crop comparison; the sign varies with the compositional anchor and the window                                                                               |
| N leaching                       | LPJ-GUESS                                     | Relative changes reported numerically; direction checked across models                                                                 | Identical irrigation settings across the two point-model scenarios leave near-zero leaching; magnitude is directional only                                                                |
| In-field soil N <sub>2</sub> O   | Relative changes from all three models        | Substitution: relative decline reported numerically; addition: LPJ-GUESS domain-scale reported numerically, cross-model direction only | Absolute magnitudes differ by an order of magnitude and are not reported; the substitution decline converges across models, while addition reverses sign in one station–model combination |
| Soil organic carbon              | Reported per model                            | Direction only; substitution sign varies with model and retention rate                                                                 | Baseline trajectories differ across models and absolute stocks are not comparable; the absolute change enters the climate account via LPJ-GUESS, contributing 4%                          |
| Irrigation amount, deep drainage | LPJ-GUESS                                     | Magnitude and direction; deep drainage as a proxy for recharge                                                                         | Demand-based irrigation; the aquifer is not modeled                                                                                                                                       |
| Evapotranspiration               | All three models                              | Direction; transpiration magnitude used for water-balance closure                                                                      | LPJ-GUESS outputs transpiration only                                                                                                                                                      |

| Quantity              | Primary reporting                       | Reporting status                                                                                   | Basis                                                                                                                        |
|-----------------------|-----------------------------------------|----------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|
| Biological N fixation | LPJ-GUESS                               | Accounting structure and direction                                                                 | Fixation varies with biomass; it does not carry conclusions across N-application states                                      |
| Climate account       | Inventory + LPJ-GUESS relative response | Reported numerically (3.0; 2.56–3.24 across the upstream and crop-season emission-factor settings) | The upstream term is model-independent; the in-field terms take the converged relative response times the inventory baseline |

### 3 Results

Throughout, each dimension is judged by its change relative to that pathway's own control. Regional magnitudes are taken from LPJ-GUESS as domain area-weighted means over the end-of-century decade (2091–2100), and directions are checked against the point-scale models at the shared stations.

#### 3.1 Four-dimensional consequences of the two pathways

The addition pathway improves the carbon, nitrogen, and food dimensions in the same direction, and its cost falls on water (Fig. 2a). With one season of summer soybean added to the post-wheat fallow window, grain dry matter rises by 38% (19–59% across the 12 climate members). This gain is attributable entirely to the new summer season. Winter wheat itself yields 6% less under the reduced N rate. Soil organic carbon and N leaching improve in the same direction; irrigation barely changes, and what declines is deep drainage, by 27%. At the shared grid cells, the three models agree in sign for grain and N leaching. For N<sub>2</sub>O they agree as well, except DSSAT at Fenhe, the addition station with irrigation (Sect. 3.4; Supplementary Material Table S1). Soil organic carbon likewise rises in all three, except that LPJ-GUESS at Luoyang, the only real addition station, gives a negative change (Sect. 3.4).

The substitution pathway cuts inputs sharply and pays on the output side. The withdrawn inputs are 252 kg N (204 from summer maize, 48 from the succeeding wheat's N cut) and 57 mm of irrigation. This is the model's own demand-based estimate (30–68 mm across the 12 climate members). Grain dry matter falls by 47% (–20% to –47% across models). The zero-N summer soybean makes up nearly 30% of the lost summer-maize output, and winter wheat yields 3% less. N leaching falls by 20%, and the three models converge on a 69–80% decline in N<sub>2</sub>O (Supplementary Material Table S1). Soil organic carbon declines by 7.6% in LPJ-

GUESS; the cross-model sign is unresolved, so we report LPJ-GUESS, whose sensitivity to residue retention is given in Supplementary Material Text S8. All of these quantities are of the same sign across the 12 climate members for both pathways, with ranges given in Fig. 2a.

The two pathways act on the aquifer in opposite directions: addition reduces recharge, substitution reduces abstraction (Table 3, Fig. 2c). The coefficient converting deep drainage to actual recharge varies with water-table depth in this region. It is near 1 in the shallow-water-table piedmont<sup>[44]</sup>, falling to 0.2–0.7 where the water table has dropped by more than 30 m<sup>[45]</sup>. Testing the range 0.3–1 leaves the sign of both pathways' net balance unchanged. The applicable cropland area within the domain is 2.5 Mha for addition and 9.9 Mha for substitution. Scaled by this area, the domain-wide net gain under substitution is 7–20 times the net depletion under addition. Under the overdraft-belt partition of Sect. 2.1, the water responses of both pathways are stronger inside the belt. Addition cuts deep drainage by a median of 40% inside versus 27% outside. The irrigation withdrawn under substitution amounts to 64 mm inside versus 47 mm outside (Supplementary Material Text S16.3).

Table 3 | Net groundwater balance of the two pathways and their food costs. Reference member MRI-ESM2-0 × SSP2-4.5, domain area-weighted means, 2091–2100; 12-member range in Fig. 2; water in mm/yr, grain in Mg DM/ha

| Pathway      | Recharge side<br>(deep<br>drainage) | Abstraction<br>side<br>(irrigation) | Net balance<br>(reduction<br>factor 0.3–1) | Grain dry<br>matter | Crude protein      | Recharge cost<br>per Mg protein |
|--------------|-------------------------------------|-------------------------------------|--------------------------------------------|---------------------|--------------------|---------------------------------|
| Addition     | –45.7                               | –0.8                                | –45 to –13                                 | +2.33 (+38%)        | +113%              | 13–44 mm                        |
| Substitution | +28.1                               | –56.7                               | +65 to +85                                 | –7.83 (–47%)        | +3.3% <sup>a</sup> | not applicable                  |

Net balance = change on the recharge side – change on the abstraction side, with the reduction factor applied to the recharge side. Both sides are proxies and indicate direction and magnitude only. Substitution's protein change is close to zero, so this ratio degenerates and is not applicable. Crude protein column: the +113% for addition is the area-weighted per-cell median; the corresponding system-level protein-total ratio rises by about 114% (Sect. 3.1). <sup>a</sup> System-level, end-of-century window, net of the protein penalty from the succeeding wheat's N cut. Positive for the reference member and –6% at the four-GCM median under the same scenario, with only one of the four GCMs (MRI-ESM2-0) positive. Across the 12 climate members the range is –30% to +51%, turning from negative to positive with emission scenario (Sect. 3.1, 3.2). Sensitivity to the compositional convention is given in Supplementary Material Text S7.

Food is next accounted as grain crude protein, converting simulated grain dry matter with a fixed dry-basis composition. The composition is soybean 39.9%, summer maize 10.5%, and winter wheat 14.5% (all as  $N \times 6.25$ ). Under addition, the system-level protein total rises by about 114%, in the same direction as dry matter. The substitution pathway's crude-protein cost depends on the CO<sub>2</sub> scenario. Raising CO<sub>2</sub> alone shrinks this cost in all three crop models, but once climate is varied together with CO<sub>2</sub>, whether substitution loses protein is set by each model's baseline. DSSAT increases throughout, and APSIM stays close to parity (−5.5% to +17.5%). The reversal from a decline under low emissions to a gain under high emissions appears consistently only in LPJ-GUESS. There, all four GCMs agree (−25% under SSP1-2.6, +40% under SSP5-8.5 at century's end). The break-even CO<sub>2</sub> concentration, about 580–670 ppm, is set by that model's photosynthesis parameterization (Table 3; sensitivity to the compositional convention in Supplementary Material Text S7).

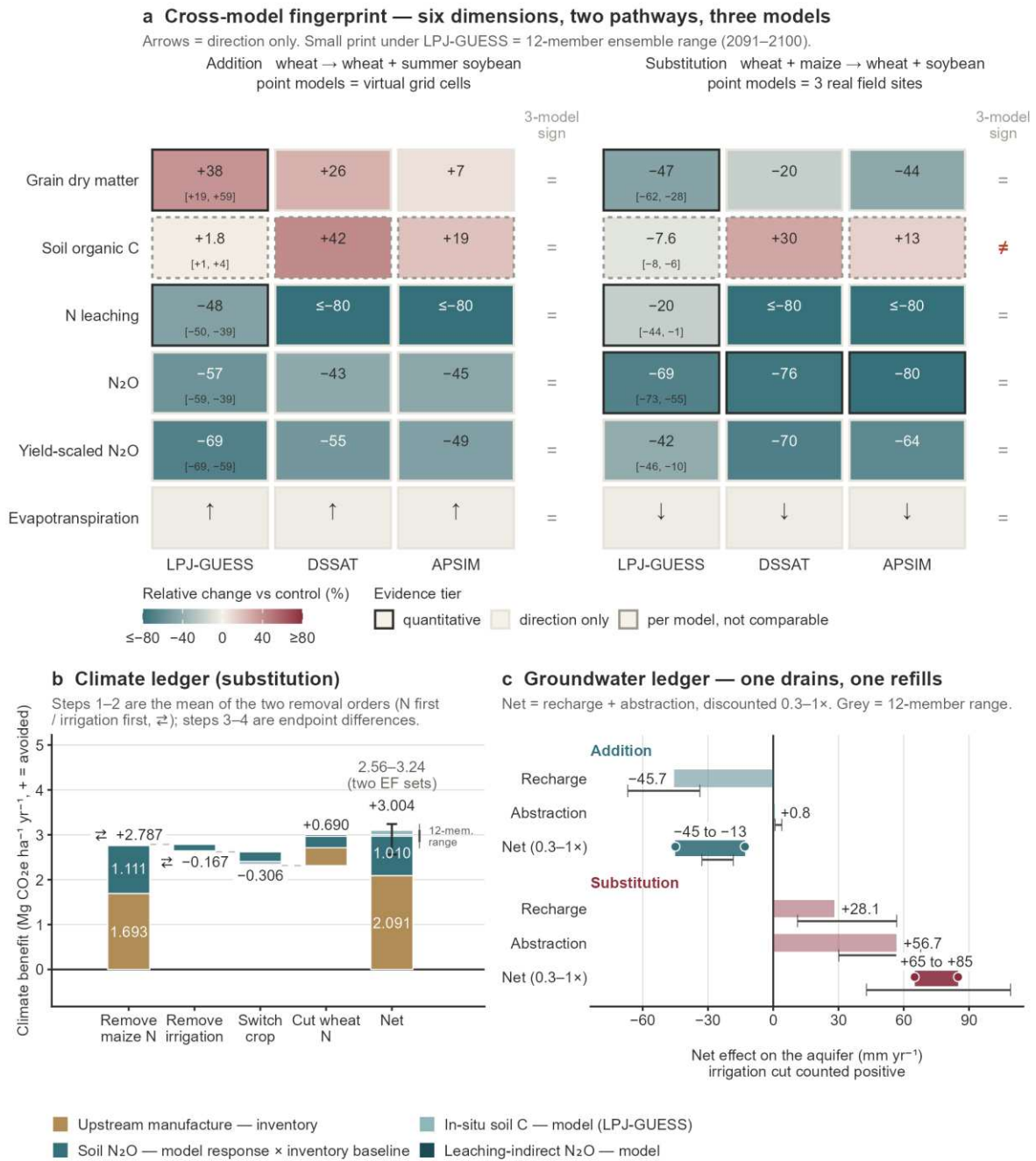


Fig. 2 | Three ledgers: over 90% of the substitution pathway's climate benefit comes from N withdrawal, the two pathways act on groundwater in opposite directions, and of the six dimensions, grain and N<sub>2</sub>O relative changes agree across the three models. Bars and dots are the reference member (MRI-ESM2-0 × SSP2-4.5); thin grey whiskers span the 12 climate members (4 GCMs × 3 SSPs): the net benefit in b (2.84–3.11), and in c the recharge- and abstraction-side quantities, with the net-balance whisker spanning the 12 members × reduction factors 0.3–1. a, Relative changes (%) in six dimensions, 2091–2100, for LPJ-GUESS (domain area-weighted) and the two point-scale models (station means); color scale truncated at ±80, out-of-range cells marked ≤/≥ (point-scale models' raw N-leaching values, -93% to -98%). Solid black frames, quantities reported numerically; dashed grey frames, reported per model; unframed, direction only. Right-edge symbols show whether the three models agree in sign. b, Four-step decomposition of the substitution pathway's climate account (Mg CO<sub>2</sub>e per hectare per year): brown, the inventory term (upstream fertilizer manufacture); teal, the model-response terms (soil N<sub>2</sub>O, in-situ soil carbon, indirect N<sub>2</sub>O from leaching). Steps marked ±

are averaged over the two removal orders; the other two are endpoint differences. Error bars span the two emission-factor settings (2.56–3.24); values in Supplementary Material Table S2. The addition pathway's account (0.84; 0.54 from the succeeding wheat's N cut, 0.30 from soybean itself) is not shown. c, Net aquifer effect: recharge side, abstraction side (irrigation reductions entered as positive), and net balance, the bar spanning recharge reduction factors of 0.3–1. Scaled by applicable cropland area (2.5 and 9.9 Mha), the net gain under substitution is 7–20 times the net depletion under addition.

### 3.2 Temporal trajectories after conversion

The four dimensions reach their plateaus at different times. The nitrogen response approaches its end-of-century level within little more than a decade, whereas soil carbon, and the substitution pathway's protein, take more than half a century (Fig. 3a–e). Under addition, grain, protein, and leaching plateau within ten years of adoption, the N<sub>2</sub>O decline deepens before partially rebounding, and the soil carbon gain only levels off in the 2070s. Under substitution, the N<sub>2</sub>O decline deepens from the conversion onward, bottoms out in the 2070s, and then eases slightly. The soil organic carbon gap keeps widening in the opposite direction, the control accumulating continuously while the intervention stays nearly flat. The grain and protein costs narrow over time. Crude protein falls first and then rises. Under the high-emission scenario it stays at or above zero from 2057 onward. Under the intermediate scenario it is still –6% at the four-GCM median by century's end (+3.3% for the reference member, Table 3). Under the low-emission scenario it holds near –25% throughout (Fig. 3b; decade-by-decade values in Supplementary Material Text S22.1).

Most of the N<sub>2</sub>O decline is realized in the very year N is withdrawn and holds steady over the following eighty years. Switching crops partly reverses the decline, and the rebound narrows as the soil N pool re-equilibrates; the soil carbon loss, too, arises mainly at the crop-switch step. Switching crops also pushes N leaching back above the control, and the succeeding wheat's N cut presses it back down (decade-by-decade values per step in Supplementary Material Text S22.2). Under the high-emission scenario, the N<sub>2</sub>O decline in both pathways narrows from the 2060s onward. By the end of the century it reaches –40% for addition and –57% for substitution (–58% and –71% under SSP1-2.6). Addition's soil carbon gain is largest under this scenario (+1.2 Mg C/ha, versus +0.4 under SSP1-2.6; Fig. 3c, e).

The zero-N system can be sustained. With N withdrawn but no crop switch, summer maize yields decline continuously while the crop depletes soil N, reaching 0.45 of the fertilized control by century's end (Fig. 3f). In the two point-scale models the ratio is 0.28–0.46 at the three irrigated stations, and the rainfed western-Henan station is unchanged (Supplementary Material Text S28). Its non-symbiotic N fixation amounts to only 4.9 kg N

per hectare. Entirely unfertilized summer soybean yields rise by 73% in LPJ-GUESS, increasing under all three emission scenarios (Fig. 3f). The two point-scale models disagree: APSIM shows small increases at most stations, DSSAT decreases at most (Supplementary Material Text S21.4). In-season fixation delivers 85 kg N per hectare to the plant, slightly below the 92–150 kg N measured for full-season soybean in this region. This is consistent with the shorter post-wheat season (median 107 days); in-season fixation plus N uptake covers the N removed in the grain (N balance in Supplementary Material Text S21.3). A micro-plot trial on a residual-N gradient after wheat in this region points the same way: yields of unfertilized summer soybean rise with residual N<sup>[46]</sup>.

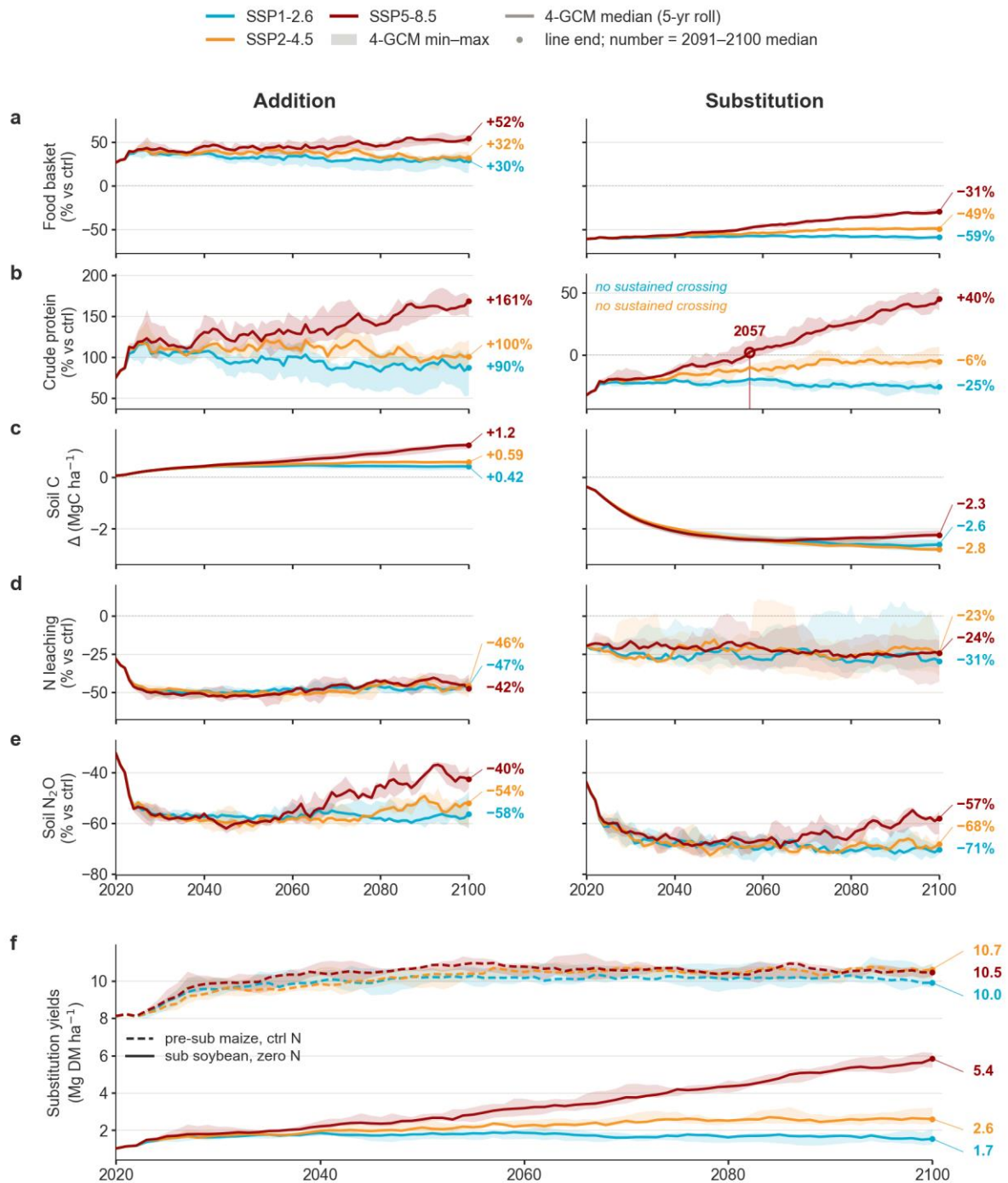


Fig. 3 | Addition gains plateau within a decade of adoption; the costs of substitution narrow over time while its soil-carbon loss keeps growing, and only under SSP5-8.5 does its crude-protein change turn and stay positive. LPJ-GUESS domain responses, 2020–2100, relative to the paired control (cropland-area weighted), left column addition, right column substitution: a, two-crop grain dry matter; b, system crude protein; c, soil organic carbon (absolute difference, Mg C/ha); d, nitrogen leaching; e, soil N<sub>2</sub>O. Lines are the median of four climate models (MRI-ESM2-0, MPI-ESM1-2-HR, GFDL-ESM4, CMCC-ESM2) after a 5-year centered running mean of each member (10-year for substitution nitrogen leaching); bands span the four models; colors mark SSP1-2.6, SSP2-4.5, and SSP5-8.5. Dots mark the end of each drawn line; numbers give the 2091–2100 mean (median of the four models), the window used throughout the text. In b (substitution) the open circle marks the year from which the SSP5-8.5 median stays at or above zero (2057); the SSP1-2.6 and

SSP2-4.5 medians do not cross zero durably before 2100. Panel b uses separate y-axes for the two pathways. f, Substitution yields behind the protein response: summer maize under control fertilization (dashed) and zero-N summer soybean (solid), Mg dry matter per hectare, by scenario.

### 3.3 Stepwise decomposition of the climate account

Of the substitution pathway's climate benefit of 3.0 Mg CO<sub>2</sub>e per hectare per year, almost all comes from the withdrawn N fertilizer. The crop switch itself is close to zero (Fig. 2b). Upstream fertilizer manufacture is an inventory calculation (Sect. 2.4) and does not depend on process-based models. The three in-field terms (soil N<sub>2</sub>O, in-situ soil carbon, and indirect N<sub>2</sub>O from leaching) are carried by the process-based models. Soil N<sub>2</sub>O is taken as the models' converged relative decline times the inventory baseline (components in Fig. 2b; other conventions in Supplementary Material Text S18.1). The full account falls between 2.56 and 3.24, a range arising from the respective values of the upstream and crop-season emission-factor sets. Under the default emission factors, the 12 climate members give 2.84–3.11, so the climate benefit is not sensitive to scenario. A pure inventory calculation gives 2.99, which shares its baseline with this account and therefore amounts to a consistency check.

The stepwise removal locates the benefit in a single step. Withdrawing summer maize N accounts for over 90%, of which 60% is upstream manufacture. The succeeding wheat's N cut comes next, while irrigation withdrawal and the crop switch are small negatives (Fig. 2b). The crop switch is negative because N fixation adds N to the soil and raises in-field N<sub>2</sub>O. APSIM shows a uniform increase at its four stations, and DSSAT shows three increases and one decrease (Supplementary Material Table S37). The addition pathway's climate account, read for magnitude, is 0.84: 0.54 from the succeeding wheat's N cut and 0.30 from soybean introduction itself. The same crop-switch step lowers N<sub>2</sub>O under addition, as the soybean takes up mineral N and its transpiration dries the soil.

The benefit structure of N withdrawal is corroborated by the N-fertilizer sweep (Fig. 4). As winter wheat N is stepped down from 264 to 144 kg N, the three models agree: the benefit of reduction is steep and its cost gentle. Returns diminish beyond 192–168 kg N, consistent with the field synthesis showing N<sub>2</sub>O rising supralinearly with N rate<sup>[47]</sup>. In the reverse direction, adding 0–120 kg N to summer soybean raises N losses substantially while the food basket rises by at most 10%. A domain-scale control that keeps summer maize but lowers its N rate from 204 to 144 marks the dividing line for soybean introduction. By the end of the century, N<sub>2</sub>O under this control falls by 34%, achieving 40–50% of the substitution pathway's decline while retaining the maize crop. The cost is offsetting the maize yield gain (quantities in Supplementary Material Text S17). Soybean introduction delivers the remaining decline,

output sustained by fixation under zero N and domestic soybean, with the cost falling on grain dry matter.

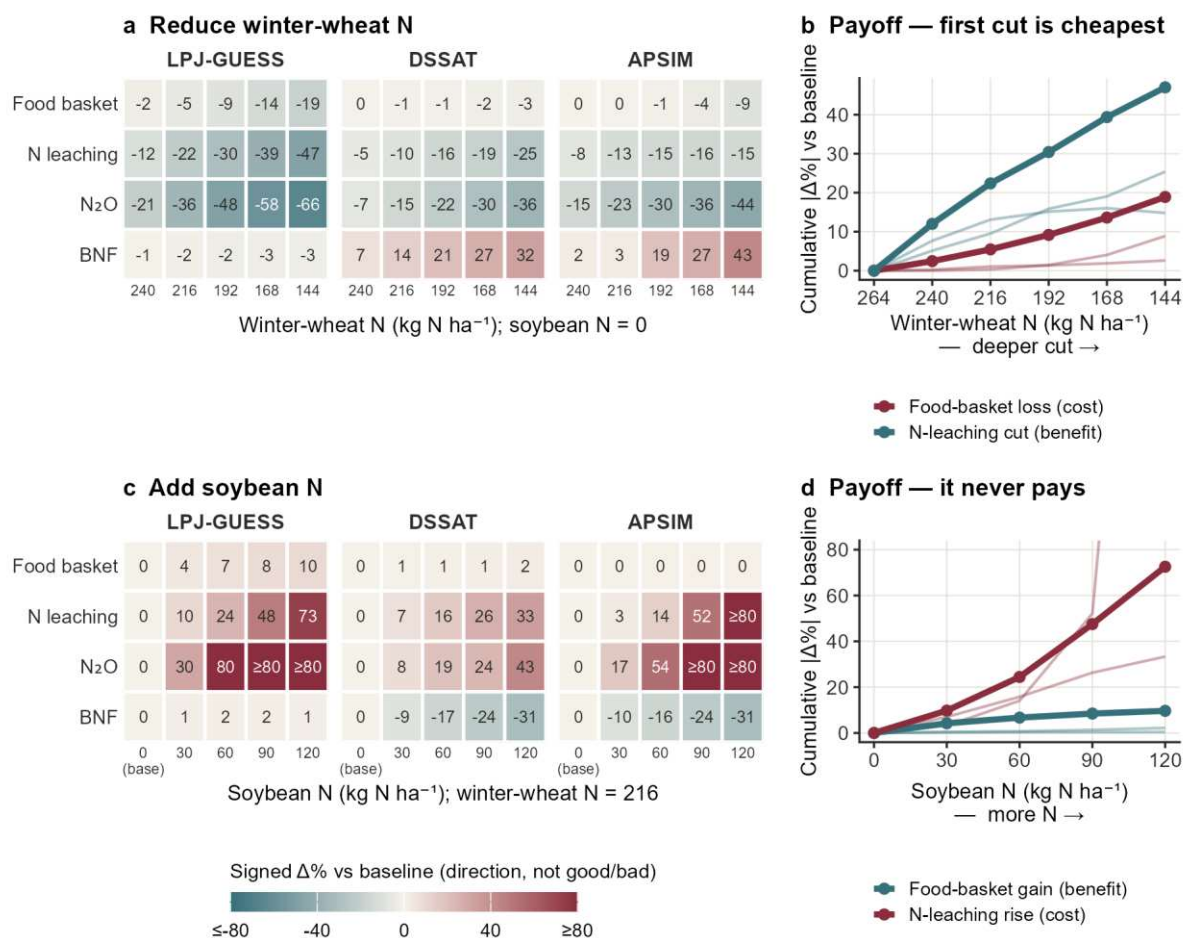


Fig. 4 | N-fertilizer sweep: the first reduction step delivers the steepest benefit at the gentlest cost, and adding N to summer soybean only increases N losses. a, b, Reducing winter-wheat N from 264 to 144 kg N; c, d, adding 0–120 kg N to summer soybean (exploratory). In a, biological N fixation in the two point-scale models rises as N is reduced, while LPJ-GUESS moves the opposite way within 3%, its fixation tracking biomass rather than N availability (Supplementary Material Text S4). In c, fixation in the two point-scale models falls as N is added, while LPJ-GUESS rises slightly (about 1%). Values are seven-station medians; the baseline column 264 is omitted in a (its  $\Delta\%$  is identically zero) and the baseline column 0 is kept in c. Colours encode direction, not valence (cool, decline; warm, increase), so a warm cell is favourable for biological N fixation and unfavourable for N<sub>2</sub>O and N leaching; out-of-range cells are marked  $\leq/\geq$ . b, d, Marginal returns: cumulative declines in N leaching (benefit) and in the food basket (cost); thick line, LPJ-GUESS; thin lines, DSSAT and APSIM. In b the benefit stays steep while the cost accelerates beyond about 192–168 kg N; in d the cost rises from the first increment, so 0 kg N is optimal (APSIM's leaching spike is truncated). The small fixation response of LPJ-GUESS at low N reflects caps on its fixation potential and carbon cost.

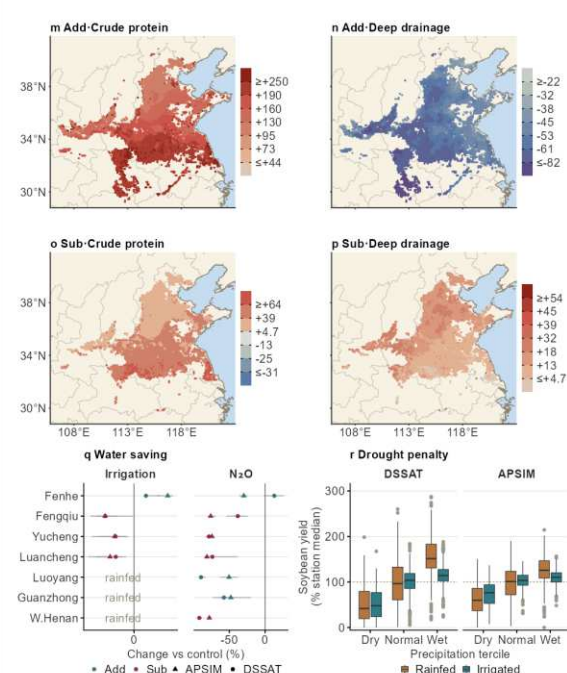
### 3.4 Spatial consistency of the conclusions and interannual risk

The key signs of the two pathways are nearly uniform across the domain; the only quantity that splits with scenario is substitution-pathway crude protein (Fig. 5). Grid cells share the same climate member and uniform management settings and are spatially autocorrelated, so counts of same-sign cells are a descriptive measure of domain-wide consistency, not independent replicates. Under addition, crude protein is positive in every cell where it is defined, and deep drainage and N leaching each decline in over 99% of cells. Under substitution, deep drainage rises in 99.5% of cells, and soil organic carbon is negative nearly everywhere in LPJ-GUESS (domain summaries in Supplementary Material Table S3). The spatial pattern of substitution-pathway crude protein shifts with scenario. Under SSP2-4.5, positive and negative cells hold comparable shares, with the negatives concentrated in the north and the four GCMs disagreeing in sign at nearly half of the cells. Under SSP1-2.6 nearly the whole domain is negative, and under SSP5-8.5 nearly the whole domain is positive (Fig. 5c, i, o). The per-cell output ratio inherits the sequential crop calendar (summer sowing dates follow the winter wheat harvest date). So Fig. 5 is read only for the spatial split of signs and does not identify individual fields.

Output risk in adverse years varies with the irrigation regime. With dry and wet years defined by within-station growing-season precipitation terciles, dry-year yields are 0.25–0.45 of wet-year yields at rainfed stations. Dry-year yields are 0.43–0.71 of wet-year yields at irrigated stations, across the two models and three scenarios (Fig. 5f). Grouping by pathway instead overlaps closely with this split, because among the seven stations addition is mostly rainfed and substitution mostly irrigated. So the difference is read by irrigation regime (Supplementary Material Text S14). Under the high-emission scenario the dry-year penalty is largest in DSSAT (a rainfed dry-to-wet ratio of 0.28, 0.38 under SSP1-2.6) and does not vary with scenario in APSIM. Under a threshold fixed at 2020–2049, the frequency of dry years in 2071–2100 is similar across the three scenarios and does not increase with warming (Fig. 5 caption). At the site scale, the three substitution stations with irrigated controls consistently save water under both models and all three scenarios. Fenhe, the only addition station with an irrigated control, consistently uses more water. Whether water is saved is therefore set by the pathway. The relative decline in soil N<sub>2</sub>O holds across the other six stations and both models. The only exception is DSSAT at Fenhe, where 10 of 12 climate members show an increase (Fig. 5e).

Post-wheat double cropping can be reproduced at a real station. The rainfed double-cropping station Luoyang has been in operation since 2009<sup>[28]</sup>. At this station, both DSSAT and APSIM complete the wheat season and the soybean season within the same year under

SSP2-4.5



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block, maps show 2091–2100 change relative to the paired control for the addition (top row) and substitution (bottom row) pathway: crude protein (%) and deep drainage (mm per year, absolute difference). Map color is the median of four GCMs (MRI-ESM2-0, MPI-ESM1-2-HR, GFDL-ESM4, CMCC-ESM2) in each  $0.1^\circ$  cell; hatching marks cells where fewer than four GCMs agree in sign with that median. Each variable has one color scale shared by the three scenarios (breaks from pooled quantiles, rounded). Side panels: seven-station point-model (DSSAT, APSIM) set of 4 GCMs  $\times$  this scenario. e, k, q (water saving): each point is the per-station, per-model median across the 4 GCMs of the change in irrigation water and N<sub>2</sub>O relative to the control (2091–2100 means); the thin grey whisker is the 4-GCM min–max range. f, l, r (drought penalty): summer-soybean yield (% of station median) by growing-season-precipitation tercile computed within each scenario and station, pooling all 4 GCMs  $\times$  all years (2020–2100); boxes pool the same set. Irrigated sites (control irrigation, 2091–2100 mean, ensemble median, mm): Fengqiu 310, Luancheng 388, Yucheng 352, Fenhe 258; Luoyang, Guanzhong, and western Henan are rainfed. Under a fixed threshold set by each station's 2020–2049 terciles, the dry-year frequency in 2071–2100 is 32% (rainfed) and 32% (irrigated) under SSP1-2.6, 34% and 35% under SSP2-4.5, and 33% and 32% under SSP5-8.5.

### 3.5 Sources of variance in the station-scale responses

At the seven stations, we decompose the end-of-century change across 36 members (3 crop models  $\times$  4 climate models  $\times$  3 scenarios) with a three-factor variance decomposition<sup>[48]</sup> (Fig. 6). Under substitution, the level of the response for grain and crude protein is set mainly by the crop model (72% and 69% of variance). The response to scenario is set mainly by the emission scenario (70% and 39%), and the interaction in crude protein is set mainly by the crop-model  $\times$  scenario term (27%). The three crop models agree on the direction of the scenario effect but not on its magnitude. The reversal from a decline to a gain occurs only in LPJ-GUESS (Sect. 3.1). The level of N<sub>2</sub>O is likewise set mainly by the crop model (46%), with more than half of the response attributed to interaction. Both the level and the response of irrigation are dominated by the climate model and its interaction (the crop models differ by less than 3%). This reflects each climate model's specific weather. Under addition, apart from the level of irrigation (72% crop model), the interaction term accounts for 55–83% of variance, with no single factor dominant. The design is saturated, so the third-order interaction is the residual. Grain and crude protein are of the same, positive, sign across all 36 members. The full variance shares, including interaction terms, are given in Supplementary Material Fig. S3.

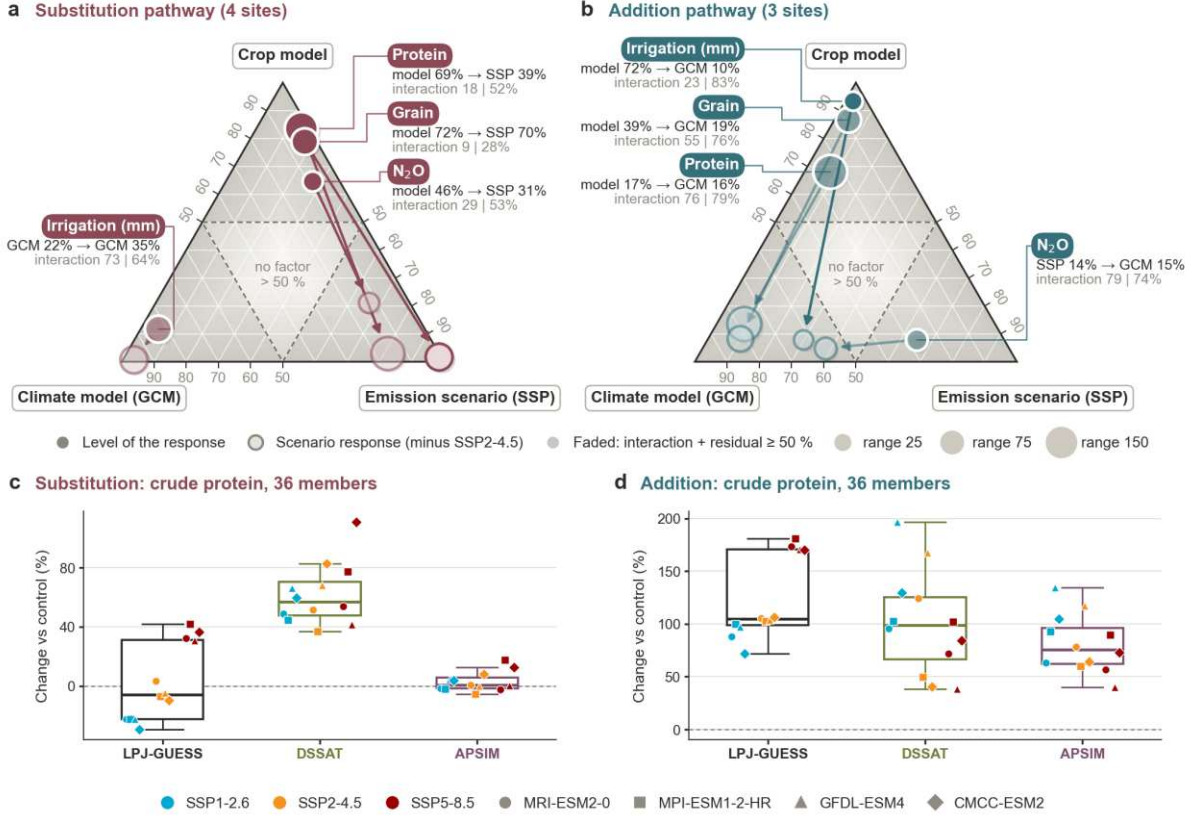


Fig. 6 | At the seven point-model sites, the crop model sets how large the protein response is; the emission scenario sets which way it moves. a, Substitution and b, addition pathway. Each quantity is placed by how the three main effects, crop model (LPJ-GUESS in the grid cell containing each site, DSSAT, APSIM), climate model (MRI-ESM2-0, MPI-ESM1-2-HR, GFDL-ESM4, CMCC-ESM2), and emission scenario (SSP1-2.6, SSP2-4.5, SSP5-8.5), divide the variance of its 36 end-of-century values (2091–2100, intervention relative to its paired control; balanced three-factor analysis of variance<sup>[48]</sup>). The ternary axes show only these three main-effect shares, renormalized to 100%; the interaction share (including third-order interaction; the design is saturated, so there is no separate residual) is given under each label (level | response), and points where it reaches 50% or more are drawn faded. Filled circles decompose the level of the response; light circles decompose the scenario response, i.e. each crop-model  $\times$  climate-model series minus its own SSP2-4.5 value, which removes each model's baseline offset. For substitution protein, the crop model explains 69% of the level but 1% of the scenario response, of which the scenario explains 39%. In the addition pathway interactions dominate (55–83%). Circle size scales with the range of the 36 values. Shaded corners: one factor explains more than half of the main-effect variance. c, d, The 36 crude-protein values behind the protein entries, by crop model; color, scenario; shape, climate model. Sites are blocks (values averaged over the pathway's sites before the decomposition); protein, grain, and N<sub>2</sub>O as % change, irrigation as absolute difference (mm per year); N leaching is not shown because its control is near zero at several sites. Shares including interaction terms are given in Supplementary Material Fig. S3.

## 4 Discussion

### 4.1 The baseline cropping slot sets which resource bears the cost

Field trials and model assessments have credited the effect of introducing soybean to the legume itself. The four quantities whose signs reverse between the two pathways of this paper indicate that what matters is the use of the summer window before conversion. Nitrogen leaching illustrates this most clearly. Substitution withdraws five times as much N as addition, yet its leaching decline (−20%) is smaller than addition's (−48%). The leaching of the two baselines is likewise inverted. The bare summer soil is flushed directly by the rainy season, whereas the substitution baseline receives 77% more N and carries a maize cover. Yet it leaches less than the addition baseline. Addition places a season of crop on bare soil. Evapotranspiration rises and deep drainage falls by 27%, so less N and less water leave the profile together; substitution exchanges irrigated maize for rainfed soybean. Transpiration falls by 149 mm, more than the 57 mm of irrigation withdrawn. Deep drainage instead rises by 40%, cancelling half of the concentration effect that N withdrawal would otherwise deliver. Year type amplifies this: addition cuts the largest absolute amounts in the heaviest-leaching years, while substitution overtakes its control mostly when the control itself leaches little. This happens in ten years out of eighty, with a median excess of 2 kg N per hectare (Supplementary Material Text S22.1). In the two point-scale models the irrigation settings of the two scenarios are identical and the evapotranspiration response is small, so leaching declines far exceed the proportion of N withdrawn. The three models' leaching magnitudes therefore diverge even as their directions agree. Seen this way, the nitrogen benefit of addition is chiefly the effect of having a crop intercepting water in summer. Cover crops generally reduce leaching with no significant difference between legumes and non-legumes<sup>[14]</sup>. What is unique to soybean is obtaining protein without applying N. For the fallow window of the winter wheat belt, fill the window first, and only then weigh the choice of crop.

The same logic explains the sign of N<sub>2</sub>O at the crop-switch step. The legume adds N to the soil. Entering a maize field where fertilization and irrigation have been withdrawn and mineral N is low, it raises in-field N<sub>2</sub>O. Entering a wheat field left bare over summer, where mineral N accumulates in the fallow, the soybean takes up mineral N and its transpiration dries the soil, and N<sub>2</sub>O falls. Legume N<sub>2</sub>O comes mainly from residues and soil N turnover, with the fixation process itself contributing little<sup>[49]</sup>. Whether it rises or falls depends on whether the soil it enters is in N surplus or N deficit<sup>[50]</sup>. The same soybean should produce opposite N<sub>2</sub>O signs in the soybean season on fallow land versus high-N maize land. This is a prediction that a side-by-side trial on the two baseline types could test directly. The soil carbon sign, likewise, is more plausibly set by the baseline. What substitution removes is the domain's highest-biomass crop. Summer maize returns more residue carbon than summer

soybean; the LPJ-GUESS decline is larger at the 90% retention rate (10.3%) than at 25% (7.6%). The two point-scale models also turn partly negative at the higher retention. The higher the residue return, the more certain the soil carbon cost of substitution, and the 55–70% measured in this region falls between the two settings. Addition puts a season of biomass onto bare fallow, and soil organic carbon rises in all three models (Sect. 3.1).

Winter wheat's response to the same N cut (264→216) also varies with the preceding crop. The high-N summer maize of the substitution baseline leaves residual N, and the succeeding wheat yields 3% less. The addition baseline leaves the summer window empty, and wheat yields 6% less. No legume N credit operates in the models: with or without a soybean predecessor, the wheat penalty from the same N cut differs by less than one percentage point. This is consistent with reviews finding the net soil-N contribution of grain legumes often non-significant<sup>[15]</sup> and with field observations of post-soybean wheat in this region<sup>[51]</sup>. The addition pathway's climate account is under one-third of substitution's, and two-thirds of it comes from the bundled wheat N cut (Sect. 3.3). This is a cut the model pays for through lower wheat yields. Farmers do apply less N after soybean<sup>[4]</sup>. This paper builds that practice into its scenarios, and within the models its agronomic basis comes from the fertilizer N left by the preceding crop. The signs and magnitudes measured under one pathway are set by its baseline and do not transfer to the other. The substitution pathway's soil carbon loss is still widening at 2100, so the eighty-year window yields a lower bound. The protein sign is decided by a single ratio, the protein-parity threshold: once soybean grain reaches about 0.27 of the maize grain it replaces, protein is at parity. The ratio of crude-protein content coefficients is 0.263, about 0.27 once the succeeding wheat's N cut is taken into account. The ratio in this paper takes the fertilized summer maize of the substitution baseline as its denominator. That crop's yield rises from 9.30 Mg per hectare in the adoption period to 10.71 at the end of the century (dashed line, Fig. 3f). For the reference member the ratio rises from 0.19 to 0.28, the gain coming from zero-N soybean increasing its yield by 70% while fertilized maize gains only 15%. This is in the same direction as the difference seen in free-air CO<sub>2</sub> enrichment experiments, where C<sub>3</sub> crops gain and C<sub>4</sub> maize does not<sup>[52]</sup>. The ratio rises with the CO<sub>2</sub> scenario, and the reversal from a decline to a gain occurs only in LPJ-GUESS (Sect. 3.1). The break-even point is set by that model's photosynthesis parameterization. Whether the crop switch can avoid a protein cost therefore depends on whether soybean breeding can keep up with the CO<sub>2</sub> dividend it receives. Every 10% gain in soybean yield improves system protein by roughly six percentage points.

## 4.2 The climate benefit stems from N withdrawal; soybean sustains the zero-N system

Soybean expansion and agricultural emission reduction sit side by side in the policy narrative<sup>[53]</sup>, with the agronomic rationale that legume fixation can substitute for fertilizer N<sup>[12][13]</sup>. The decomposition in this paper splits that narrative into two parts. Over 90% of the substitution pathway's climate benefit comes from withdrawing summer maize N, 60% of which is set by fertilizer manufacture alone. The process-based models add three points. First, the in-field responses point the same way as the fertilizer-manufacture term. The three models converge on soil N<sub>2</sub>O, and the soil carbon loss contributes only 4% of the climate account. Second, the crop-switch step itself is close to zero, slightly negative under substitution and slightly positive under addition; both outcomes follow from the soil N-and-water status mechanism of Sect. 4.1. Third, the zero-N counterfactual shows that the system can be sustained (Sect. 3.2). Withdrawing fertilizer without switching crops leaves summer maize continuously depleting soil N. In zero-N summer soybean, in-season fixation plus uptake covers the N removed in grain. This is consistent with the field synthesis finding that where yields fall well below about 4.5 Mg per hectare, soybean fixation broadly meets N demand. Added N in that regime mostly displaces fixation rather than raising yield<sup>[54][55][56]</sup>. The soybean yields of this paper sit below that threshold.

The "N cut without soybean" control (Sect. 3.3) already achieves 40–50% of the substitution pathway's N<sub>2</sub>O decline while leaving soil N untouched. The cost is offsetting the maize yield gain. The N-fertilizer sweep (Sect. 3.3) gives the same shape. Stepping winter wheat N down to 192–168 kg N, N losses fall sharply while yields barely move, in line with the supralinear N<sub>2</sub>O response to N rate<sup>[47]</sup>. This also matches field results in this region showing yields approaching a plateau beyond 185 kg N<sup>[57]</sup>. The yield cost of the 264→216 step is nearly zero in the two point-scale models and 3–6% in LPJ-GUESS (Sect. 4.1). N reduction is a policy lever that can be operated on its own. Field practice at the scale of millions of farm households in this region has already shown that cutting N by 10–20% does not lower yield<sup>[58]</sup>. The distinct contribution of introducing soybean is sustaining output, and producing soybean, at zero N, with the cost falling on grain dry matter. The greenhouse-gas decline and protein gain of the soybean rotation in the six-year Luancheng trial<sup>[19]</sup> can be decomposed on this basis. Such designs bundle the N cut and the legume in one treatment, and most of the benefit is attributable to the former. The emission cuts from N withdrawal arrive in the very year of conversion, while the soil carbon cost takes half a century to surface. So short-window assessments are biased toward substitution.

### **4.3 The groundwater account: recharge and abstraction sides are asymmetric, and overdraft belts favor substitution**

Groundwater studies in this region have long used recharge minus abstraction as a water-table indicator<sup>[59]</sup>. Cumulative depletion stands at 160 km<sup>3</sup><sup>[5][6]</sup>. The point-scale models' substitution results point the same way as this paper. Substituting soybean for summer maize lowers evapotranspiration and its water footprint, easing groundwater-overdraft pressure<sup>[21]</sup>, and regional substitution rotations slow water-table decline<sup>[22]</sup>. This paper adds two things: both pathways are brought into one balance, with the recharge side and the abstraction side listed separately. The separation carries physical meaning. A change on the recharge side must pass through the vadose zone before reaching the aquifer. The reduction factor decays from near 1 to 0.2–0.7 as the water table falls (Sect. 3.1). A change on the abstraction side, by contrast, acts on the aquifer directly, with no reduction applied. The water effects of the two pathways travel different physical routes. By this logic, the deeper the water table within an overdraft belt, the more the recharge cost of addition is attenuated, while the irrigation saving of substitution is preserved intact. The net-balance ranges in Table 3 are this asymmetry made visible. Substitution also saves more irrigation inside the belt than outside (Sect. 3.1), so within the groundwater-overdraft belt soybean should enter through substitution. Under the zone-specific discount (0.3 inside the belt, 1 outside), addition's net balance is –13 mm/yr inside the belt and –45 mm/yr outside, against +77 and +74 for substitution. Substitution relies on the undiscounted abstraction side, while addition's recharge cost is discounted away by about 70% inside the belt. How much the two pathways rely on recharge versus abstraction also shifts with emissions. Addition's recharge cost deepens from –36 mm/yr under SSP1-2.6 to –59 mm/yr under SSP5-8.5 (four-GCM median), while substitution's recharge gain narrows from +45 to +13. Its net groundwater benefit therefore comes to depend mainly on the saved abstraction (+43 to +54).

The same asymmetry also decides how visible each cost is. The irrigation saved under substitution passes through the farmer's pump; it can be metered under the abstraction-control program and written down against water rights. The recharge lost under addition passes through no water meter at all, beyond the reach of the permit-based regime that governs overdraft control<sup>[8][60]</sup>. Scaled onto the 2.5 Mha where addition applies, this unmetered recharge loss amounts to 0.3–1.1 billion m<sup>3</sup> per year. This compares with a net gain of 6.4–8.4 billion m<sup>3</sup> from substitution on its 9.9 Mha. This paper uses deep drainage as a proxy for potential recharge (Sect. 4.4); the unmetered nature of the cost does not depend on the

precision of that proxy. Against the region's only multi-year field trial directly comparing the two cropping slots<sup>[18]</sup>, the modeled annual water-use decline exceeds its observed range. Once the transpiration and evapotranspiration conventions are aligned, the substitution pathway's evapotranspiration decline narrows from 149 mm to 101 mm, with the remaining gap unresolved. Water magnitudes are therefore read for direction and interval.

Interannual risk falls on the other side. The dry-year yield-loss risk of rainfed summer soybean is markedly higher than under irrigation (Sect. 3.4), and winter wheat after soybean also declines in dry years<sup>[16]</sup>. The climate and groundwater benefits of a low-input system are effectively public goods. The risk of dry-year losses, and the extra season of labor that filling the fallow window demands, fall on the household. Current soybean subsidies are paid per unit of sown area with no distinction between pathways. So inside the overdraft belt, subsidizing addition amounts to subsidizing a recharge loss that no meter ever sees. If the irrigation saved under substitution is not written down against water rights and the yield cost goes uncompensated, the groundwater benefit documented here remains at the level of accounting. The water-and-soil, emissions, and domestic-soybean ledgers give a basis for subsidies differentiated by pathway and by overdraft zone; their size depends on the weight policy gives each ledger.

#### **4.4 Increment over existing work and study boundaries**

A system comparison for the same region judged the optimized winter wheat–summer maize system best overall, with no soybean-based system ranked first<sup>[23]</sup>. This paper does not contradict it. That study compared existing systems at a single point in time, with grain tallied in tonnes. This paper instead compares the trajectory of converting from the status quo and asks which resource bears the cost. Field rotation trials<sup>[19][20]</sup> and point-scale models<sup>[21][22]</sup> each report the combined effect of one pathway. This paper adds the fallow-window addition pathway, decomposes the combined effect into N and crop, and places the two pathways side by side in one groundwater account. The same model had previously been used to optimize the spatial layout of crops across China<sup>[61]</sup>; what this paper changes is the cropping-slot structure.

This paper's conclusions hold within the following boundaries. First, the regional scale rests on one model. In this region LPJ-GUESS underestimates winter wheat absolute yields by 30–43%, overestimates summer maize by 10–30%, and carries a soil nitrate pool only 20% of measured residual nitrate. Paired differencing only bounds the resulting cancellation from above. So the relative declines in the nitrogen dimension still rest on an undersized N pool,

whose magnitude in real soils awaits field testing. Leaving yields uncalibrated cell by cell and interpreting over larger spatial entities is standard practice for regional crop models<sup>[62][63]</sup>. Second, summer soybean yields have no long-term observations under matching management to calibrate against. This region has no long-term rainfed zero-N soybean station; the adoption-period yield of 1.8 Mg per hectare is comparable to regional statistics. The end-of-century yield of 3.0 Mg (1.7–5.4 across the four-GCM medians of the three scenarios) embeds CO<sub>2</sub> fertilization and warming and should be read as a potential yield<sup>[64]</sup>. Third, continuous cropping: this paper plants summer soybean every year to 2100, in models with no soybean cyst nematode<sup>[65]</sup>, autotoxicity<sup>[66]</sup>, or phosphorus-and-potassium depletion. Published long-term soybean simulations all run shorter than 80 years<sup>[67][68]</sup>. When rerun at the seven stations with alternate-year planting, the two point-scale models show responses at roughly half the continuous-planting values, with none of the fourteen model–station combinations flipping sign. The end-of-century soybean yield and the positive protein sign are therefore to be read as an upper bound free of these constraints. Fourth, water is a proxy quantity: deep drainage is not recharge, irrigation is demand-driven, and the aquifer is unmodeled. Magnitudes are read as intervals, and directions are given by the water-balance structure. Fifth, domain-uniform N rates and a single cultivar. On cells where actual N application falls below the prescribed rate, the same withdrawal would deliver a smaller decline. The model-dependent term of the climate account is therefore biased high at the domain scale, a known direction. The effect of a single uniform N constant on simulated yields has already been diagnosed in regional applications of the same model<sup>[31]</sup>. Sixth, field implementation. Zero-N fixation presumes successful nodulation, and introducing soybean on fields rarely planted to it typically requires rhizobial inoculation. The summer maize preceding the substitution pathway is often treated with herbicides of long residual activity, whose carryover injury risk to the following summer soybean is likewise unassessed. Pests and weeds, household adoption willingness, and the economic feasibility tied to the soybean-to-maize price ratio lie equally outside the models.

Both pathways are whole-field rotations. Maize–soybean strip relay-intercropping is another route to more soybean<sup>[69]</sup>. Its trade-offs are governed by spatial processes (row ratio, border rows, and shading<sup>[70]</sup>), and building crop spatial competition explicitly into the models is the next step. Both pathways raise domestic soybean output, and substitution lowers summer maize at the same time. The net effect on import demand must pass through a trade-balance analysis, as international trade transmits it into land-use consequences in exporting regions<sup>[71][72]</sup>.

## 5 Conclusions

The gains from introducing soybean trace to the inputs withdrawn with it, and the legume's own contribution is to keep a zero-N system viable. Which window those inputs are withdrawn from decides whether the cost falls on water or on grain, and whether it can be metered. This paper placed the same season of low-input summer soybean into two common states of the post-wheat window, each with a control that maintains the pre-existing system. The changes were withdrawn stepwise. The source of the benefit, the type of the cost, and the temporal mismatch between them follow from this.

The benefit traces to the inputs withdrawn alongside the switch. The substitution pathway's climate account is almost entirely attributable to the withdrawn N, with the crop switch itself close to zero. The legume's contribution is to make the zero-N system viable rather than to cut emissions. Zero-N summer soybean raises its yield, with in-season fixation plus uptake covering the N removed in grain, whereas zero-N summer maize declines continuously while depleting soil N. N reduction is a lever that can be operated on its own, and the first increment of reduction carries the smallest cost. The distinct value of introducing soybean is protein output that survives reduction all the way to zero.

Which resource bears the cost is set by the baseline. The same season of soybean, entering the fallow window, pays in recharge. Entering the summer maize slot, it pays in grain. At the crop-switch step, the signs of N leaching, N<sub>2</sub>O, and soil carbon all reverse with the baseline. There is no answer for the effect of introducing soybean that stands apart from the baseline, and both field trials and model assessments should report their baselines. Whether substitution can avoid a protein cost comes down to whether soybean grain can reach just over one-quarter of the maize it replaces. In the models the ratio rises with the CO<sub>2</sub> scenario and crosses that threshold stably only in LPJ-GUESS; the answer rests with whether soybean breeding can close the gap.

Benefit and cost are asymmetric in both timing and visibility. The emission cuts from N withdrawal arrive in the very year of conversion, while the soil carbon cost is still widening at 2100. Short-window assessments therefore favor substitution, and validation must divide its labor: N<sub>2</sub>O by field trials of a few years, soil carbon by long-term experiments and repeated soil surveys. For groundwater, addition acts on the recharge side, attenuated by the vadose zone and passing no water meter. Substitution acts on the abstraction side, reaching the aquifer directly and lending itself to metering. Within the groundwater-overdraft belt, soybean should enter through substitution. The water-and-soil, emissions, and domestic-soybean

ledgers give a basis for subsidies differentiated by pathway and by zone; their size depends on the weight policy gives each ledger.

The design of two baselines placed side by side, with stepwise removal for attribution, transfers to any assessment that introduces a new crop into an existing cropping slot. For every winter wheat belt where well irrigation sustains high-N cropping, the case for introducing soybean starts from the current use of the window, and only then from the crop.

## **Data and code availability**

The derived data supporting this paper's conclusions are the quantities entering each figure and table. These data, all analysis and plotting scripts, the model configurations, and a per-script provenance list have been assembled into a reproduction package. An anonymized version accompanies the submission for review, and on publication the package will be deposited in a public repository (Zenodo) with a DOI. This paper made three classes of changes to LPJ-GUESS v4.0 (r10285, including the biological N fixation scheme<sup>[24]</sup>). The three classes are an extension for cropping-system conversion, per-stand carbon–nitrogen–water output, and a fix for the non-first-season dormancy defect. These changes are released with the package as patches against the official distribution, with full build identifiers and binary checksums. The scheduling parameters for within-year double cropping and the run-orchestration scripts are included as well. The raw model outputs are not deposited with the package, owing to their size (tens of GB for the gridded LPJ-GUESS output, plus several point-scale model databases). They can, however, be rebuilt in full from the model versions, configurations, patches, and forcing data carried in the package. DSSAT-CSM and APSIM are both obtainable through their official channels. The climate forcing, the land use, and the observation anchors used in model–observation comparison are all published, openly available datasets or literature. The observation anchors include the sources and provenance of station yields, evapotranspiration, and N fluxes. Their citations and dataset DOIs appear in the Methods, the References, and the validation matrix of the Supplementary Material.

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