Strong trade-offs characterise water-energy-food related sustainable development goals in the Ganges–Brahmaputra–Meghna River basin

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Abstract
The United Nations’ sustainable development goals (SDGs) set ambitious policy targets for 2030 to overcome poverty while preserving the planet. These goals are not perfectly aligned; trade-offs emerge during implementation at regional and local levels, such as in a river basin. Here, we quantify important trade-offs between water, energy, and food-related SDGs in the Ganges–Brahmaputra–Meghna River basin, a climate vulnerability hotspot, using multi-objective optimisation based on detailed water resources and crop production modelling and accounting for uncertainties in the costs of water, labour, and land. The trade-off between food production and agricultural profit is strong; the amount of people fed would be reduced by more than two-thirds, were profitability maximized. However, we do see the potential to achieve higher profitability in agriculture against limited loss of food and hydropower production and limited impact on downstream environmental flows, although continued reliance on groundwater and energy, currently unsustainable, needs to be mitigated.

1. Introduction
Concerns about environmental sustainability [1], stagnating poverty reduction [2] and rising inequality [3], among others, have led to the formulation of the sustainable development goal (SDGs). The 17 wide-ranging policy goals for 2030, meant as a shared blueprint for peace and prosperity for people and the planet, are often not mutually independent. Potential trade-offs between, for example, economic growth and responsible consumption [4] (SDGs 8 and 12), higher farm income and lower food prices for the urban poor [5] (SDGs 1 and 2), water quality and zero hunger [6] (SDGs 6, 14 and 2), or between upstream hydropower development and downstream water availability [7, 8] (SDGs 7 and 6) illustrate the complexity of development and the need for integration and cross-scale thinking [9, 10]. While the formulated goals are global, these trade-offs tend to emerge during the implementation of policies and practices at the regional and local levels, such as a river basin.

Within river basin management, trade-offs and synergies between Water, Energy, Food and Environment have been contextualised in the ‘WEF(E) nexus’ [11–13]. It is premised that a better understanding of nexus interlinkages and planning in an integrated manner can help reduce conflicts and lead to better outcomes. However, the lack of nexus coordination often has sectoral interests prevailing over the common good and local interests prevailing over basin-wide ones [14], with short-term economic goals prioritised over long-term sustainability [15] and with limited coordination between administrative departments [16]. In many river basins, agricultural subsidies on energy lead to over-exploitation of groundwater and surface water [17–19] whereas those on fertilisers and pesticides, inputs for agriculture, result in pollution [20, 21], limiting potential downstream use.

South Asia, with its large population comprising many people living in poverty, will strongly define the success of the SDG framework. The region has gone from food insecure to (near) food...
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Figure 1. Schematization of the Ganges–Brahmaputra basins with all reservoirs (type & capacity; only reservoirs with a storage capacity larger than 100 million m$^3$ are shown), and with location of the basins shown bottom right in dark grey. The navigation reservoir in orange indicates the Farakka barrage that regulates flow between the Hooghly estuary—important for shipping—and the river delta in Bangladesh, and for which we have defined our environmental flow boundary.

self-sufficient over a timespan of decades through agricultural intensification [22, 23] and the exploitation of groundwater resources [24]. Yet, it still has the largest number of malnourished children and adults in the world [25–27]. Both the region’s drylands and glacier fed river basins are considered ‘hotspots’ of climate vulnerability [28] where a stronger than global average climate signal intersects with large numbers of poor people and where concern over the sustainability of water resources utilisation has been rising [24, 29, 30].

High numbers of farmer suicides since the 1990s [31] and recent large protests against new legislative reform in India indicate a severe level of distress, with the instability of water supply impacting farm income [31–33] against a backdrop of ever smaller farm holdings [33], a deceleration in crop yield growth rates [34] and an increase in costs [32] resulting in lower margins [35]. In Bangladesh, despite progress and the improved availability of food due to increased production, 40 million people—one quarter of the population—remain food insecure [36]. While subsidies on water and energy have supported crop production and increased food security for poor rural and urban populations, they place a large burden on state finances [37] and contribute to greenhouse gas emissions [38]. An assessment of 36 water-energy-food related development indicators for five South Asian countries found the number of trade-offs almost equalling synergies [39]. A transformation to an ecologically and economically sustainable future is advocated [14, 18, 40], however, a more quantitative understanding of synergies that could spur, or trade-offs that could complicate such a transformation is still lacking.

Here, we characterise the most important SDG trade-offs, and several synergies, within the WEFE nexus in the Ganges–Brahmaputra–Meghna river basin system (figure 1), covering a large part of what is know as South Asia’s ‘wheat basket’ and ‘rice bowl’, using multi-objective optimisation, based on detailed water resources and crop production modelling. In-depth studies of the region have highlighted two-way nexus trade-offs, for example, between hydropower and downstream irrigation [8] and between energy use and irrigation [18], but broader linkages between profitability of food production—an essential link to the SDG framework—and these and other sectoral goals tend to be described qualitatively at most.

2. Methods

2.1. Multi-objective optimization of SDGs

Multi-objective optimisation allows illuminating trade-offs through exploration of nexus interdependencies [12, 41]. We applied the bio-economic model ‘WaterWise’ [42, 43], which has the specific ability to generate spatially varied patterns of measures that make best use of the available land and water resources (supplementary information for equations).

We focus on five main WEFE nexus-related indicators: (a) agricultural profit, in terms of annual net benefits of production; (b) nutritional yield in terms
of the minimum number of people that can be supported in the least productive year; (c) yield of hydropower, (d) delta environmental flow; (e) annual energy use by pumping of irrigation water (table 1). This study thereby focuses mainly on quantitative aspects of the WEF nexus, but we acknowledge that unequal access to food, micro-nutritional value or food safety issues, are often as important. In our optimisation scheme, each indicator was first optimised individually. From the results of these runs, also the worst value could be approximated. We then explored the sensitivity of these solutions by successively adding a lower bound for each indicator, taken as the 90% point on the interval between the worst and optimal values, combined with a series of sub-optimizations of the other indicators in various orders.

### 2.2. Crop production and water balance input

Crop production and water balance input for each possible land use and water management combination were taken from the crop-hydrology model LPjM, which has been adapted to the region [43, 46] (see also supplementary information). We distinguish between monsoon-season crops (locally called the kharif season) and winter-season crops (rabi season). Crop growth for 12 crops (including temperate cereals e.g. wheat, rice, maize, tropical cereals, pulses, temperate roots, tropical roots, cotton, soybeans, groundnuts, rapeseed, sugarcane and, ‘other crops’) was simulated based on the daily assimilation of carbon with crop yields calibrated against subnational statistics [46]. The irrigation demand of a crop is calculated as the minimum amount of water needed to fill the soil to field capacity and to

| Goal                                | Unit                        | Function                                                                 | Parameters |
|-------------------------------------|-----------------------------|-------------------------------------------------------------------------|------------|
| Agricultural profit                 | M USD yr⁻¹                  | Y = YLU – CLU – CLWM                                                    | Y represents total net benefits (USD yr⁻¹). YLU are the benefits of land use (USD yr⁻¹), CLU are the non-water related costs of land use and CLWM the costs of local water management measures for supporting land use, i.e. fixed and variable costs of local irrigation measures per m³ of water (USD yr⁻¹). |
| Nutritional yield                   | Number of people (M)        | Nutr = ((Prod_c × cal) ÷ loss_γ) ÷ f_diet                              | Nutr is number of people fed, in millions, with Prod_c the production per crop in ton yr⁻¹, cal is the amount of calories per ton per crop, and loss_γ the losses per crop group [44], divided by the current vegetarian dietary consumption (excluding meat) in India of 2200 kcal/person/day (FAO Food Balance Sheets, FAOSTAT). Nutr is maximized for the least productive year. |
| Yield of hydropower                 | GWh yr⁻¹                    | YP = ρ × q × g × H_net ÷ η                                          | YP represents energy generated, expressed in kWh, with ρ = density of water (kg m⁻³), q the flow through the turbines, g the gravitational constant, H_net the net head, assumed to be 0.9 times the gross head, and η the product of all of the component mechanical efficiencies (generally assumed 90% for Francis turbines of this size). |
| Energy use for groundwater pumping  | GWh yr⁻¹                    | E = ρ × q × g × H × η                                              | E represents energy used, expressed in kWh, with H the depth to groundwater and q the flow through the pump. We assume a pump efficiency of 55% and an average pumping depth of 33 m for borewells [45], and half of that for tubewells and shallow borewells. We distinguish between borewells and those wells recharged seasonally, equally distributed over the area under groundwater irrigation which is estimated at 66% of the total area under irrigation [43]. |
| Delta environmental flow (annual minimum) | m³ s⁻¹                     | —                                                                      | Flow at Farakka, close to the Indian border with Bangladesh, set at a lower bound of 1982 m³ s⁻¹ (70 000 cusecs) during the dry season. This amount is considered the minimum required to keep the Hooghly diversion towards Kolkata open for navigation and to counter salt intrusion and sedimentation in the Ganges–Brahmaputra delta. Below this amount, any available flow is equally divided between the Hooghly and the main stem towards Bangladesh following the Ganges Water Treaty. |
fulfil the atmospheric evaporative demand, accounting for losses during conveyance, distribution, and application of water, depending on the soil type.

In the optimisation, river flow dynamics—fed by LPJmL runoff and irrigation return flows—were modelled with the unit hydrograph method using a time step of one month. Reservoirs and lakes were modelled using a three-month time step. We used a 9 year period (of complete hydrological years; 2000–2009), which encompasses the natural variability in climate (dry and wet years, though not necessarily extremes) and can be considered a period in which farmers make strategic decisions. Topological schematisation involves 624 nodes connected through trajectories (figure 1), with a total of 3104 unique land use and water management combinations. Nodes, representing small sub-basins, are analogous to LPJmL grid cells.

2.3. Simulating land and water management decisions
As a baseline, we started with the present-day cropping pattern. To achieve optimum performance across goal functions (GFs), the model can apply three types of irrigation- and land-use-based demand-side decisions.

(a) dynamically reallocate water across the basin, that is, to choose between irrigation sources (surface or groundwater) and rainfed production, representing the combined operational decision by farmers and a basin manager to allocate water to the highest marginal value. Access to water resources for irrigation was constrained, with 33% of the irrigated area connected to the canal irrigation system and 66% having access to groundwater. Of those with access to groundwater, approximately two-thirds have borewells with access to deep groundwater, while the other third have only open wells accessing shallow groundwater [47]. The latter are modelled as ‘local reservoirs’ [43] that are seasonally recharged.

(b) forego planting of the second crop (grown during the winter months, the rabi season) in case of limited seasonal water resources; that is, the monsoon rains in previous months have been below average and river runoff is low and/or (local) reservoirs have not been replenished fully. Farmers can be better off leaving land fallow during the rabi season if rains have been below average [43]. Compared to water reallocation, this seasonal decision also avoids fixed (i.e. nonwater-related) costs of production.

(c) permanent conversion to fallow land for both the first and second crops in the agricultural year. This mimics the strategic decision made by a farmer to stop with a specific crop or crop rotation because it is not profitable.

We did not allow conversion from one crop to another; we assumed that current land use reflects local food preferences, market conditions, and potential based on biophysical conditions.

The supply of water is optimised through the inclusion of all existing reservoirs above 100 million m$^3$, of which there are 51 in total, as V-shaped reservoirs with linearised storage. Reservoir location and area, depth, and maximum capacity were taken from the GrAND database [48], with recent reservoirs added using information available on the GlobalEnergyObservatory.org website. Of the 51 reservoirs, 20 are used for hydropower generation; eight have a combined irrigation-hydropower function, with turbines installed at the outlet of the reservoir, and 12 are run-of-the-river hydropower stations. These 20 hydropower stations have a total potential capacity of 9655 MW (approximately a fifth of India’s and Nepal’s combined generating capacity [49]) with 2400 MW provided by the Tehri dam scheme in northern India alone, of which 1000 MW is designed as a pumped storage plant, only generating hydroelectricity during peak hours.

2.4. Cost of production
Different cost coefficients control land use and irrigation water applications. For India, cost sheets for the period 2004–2017 provide for each crop the costs of the main production factors: labour, machinery, land, water, and other inputs such as fertiliser and seeds. Many countries do not report these costs in detail. Thus, Bangladesh was assigned the same costs as the neighbouring Indian state of West Bengal, while Nepal was assigned the costs of the Indian state of Himachal Pradesh because of similar climate, agronomic and orographic characteristics. Data were corrected for inflation to 2018 price levels and averaged.

As our baseline, we opted for a comprehensive, economic approach to the monetarization of input costs, which in Indian agricultural statistics is the so-called C2 option. This option includes not only the operating costs, but also the imputed value of family labour (at an hourly rate of less than 1 USD per hour, this adds ∼20%–40% to operating costs, depending on crop and region) and fixed costs, such as the rental value of owned land (adding ∼40%–80% to operating costs). As such, it represents the total economic cost of production [50], resulting in an estimate of the net profit, and is routinely used by the Indian government and others [32, 35, 51, 52]. For comparison, we verified the main trade-offs also with the A2-concept which only includes the operating costs of cultivation and gives the gross profit.

The costs of water use were separated from the area-based cost estimates. Volumetric cost estimates are difficult to derive, with varying pricing mechanisms by country, state, province, type of water application (canal/pump), and technology [53].
Table 2. Optimization per Goal Function (GF) and for the ‘baseline’, with land use fixed according to the year 2015 and irrigation maximized for profit. Agricultural profit is the resultant of the economic yield of land use (profit minus variable and fixed costs) minus the operating cost of water use. The amount of people fed is based on a daily (vegetal) energy demand of 2200 kCal. The Delta environmental flow was kept at a lower bound of 1982 m$^3$ s$^{-1}$ at Farakka, the amount below which, as per the Ganges Water Treaty, balancing of flow between India (diverting water to the Houghly to keep it open for shipping) and Bangladesh (towards the main stem) is needed, to deal with shortage. Columns indicate individual optimizations with grey shading indicating the GF that is being optimized (optimum energy use is considered a minimunization, all other GFs are maximized). Numbers without shading are indicative as they represent only one combination of values under the optimized GF.

| # | Goal Function (GF) | Unit | Baseline | GF1 max | GF2 max | GF3 max | GF4 max | GF5 min |
|---|-------------------|------|----------|---------|---------|---------|---------|---------|
| 1 | Agricultural profit | Billion USD yr$^{-1}$ | −7.3 | 16.9 | −9.6 | −9.1 | −8.3 | −8.2 |
|   | Economic yield land use | | −6.0 | 17.1 | −7.8 | −7.9 | −7.3 | −8.2 |
|   | Cost of water application | | −1.2 | −0.3 | 1.8 | 1.2 | 1.1 | 0.0 |
| 2 | Nutrition | Million people fed | 583 | 199 | 585 | 194 | 193 | 140 |
| 3 | Hydropower yield | GWh yr$^{-1}$ | 9198 | 7174 | 7282 | 21748 | 7100 | 7128 |
| 4 | Environmental flow | m$^3$ s$^{-1}$ | 1982 | 1982 | 1982 | 1982 | 2870 | 1982 |
| 5 | Energy use by irrigation | GWh yr$^{-1}$ | 14124 | 3262 | 23337 | 12560 | 12157 | 0 |

Given the uncertainties and multiple types of costs, we simplified cost of water use for a farmer by differentiating by type of irrigation; a fixed 0.01 USD m$^{-3}$ for abstractions from wells in shallow aquifers that are recharged seasonally, and 0.02 USD m$^{-3}$ for groundwater abstractions from deep borewells. We subsequently tested for a range of groundwater costs from 0.01 to 0.04 USD m$^{-3}$ for deep borewells and half that for wells in shallow aquifers.

Annual, national-level crop prices needed to calculate the value of crop production and the marginal value of irrigation water were taken from the database of the Food and Agriculture Organisation of the United Nations (FAOSTAT) [54] for the period 2000–2018. Crop-based weighted averages were derived, with weights by number of years before 2018, thereby giving higher importance to more recent price levels while simultaneously accounting for historic price fluctuations. For India, FAOSTAT did not record price data after 2009 and time series were supplemented with minimum support prices, as reported by the Indian government.

3. Results

3.1. Exploring the limits to optimizing individual SDGs

Under near-present land use, agricultural net profits are negative in large parts of the basin (table 1, ‘Baseline’). Many crops, especially rice, generate losses when taking into account all production costs. An exception is the cultivation of wheat, with profit levels attributed to the steep increase in minimum support prices combined with subsidised inputs [31, 32, 34]. Energy use for pumping groundwater to sustain production is high, at over 14 000 GWh yr$^{-1}$, and of the same order of magnitude as the amount generated by the main hydropower plants in the basin (table 2), which underscores the magnitude of energy consumption by agriculture. In India, approximately 20% of electricity is used in agriculture, mainly for pumping groundwater [14, 55]. Without groundwater, rainfall and surface water alone would be insufficient to sustain a profitable yield in large parts of the basin and cropping intensity would decrease (figure 2(a)-GF5), and both the amount of production and the net profit of agriculture would be reduced. Despite the negative net profits, this land and water use provides nutrition in terms of available kcal for almost 600 million people or two-thirds of the total population in these basins.

Optimization of agricultural profit (GF1 maximized) by reducing costs, only planting those crops that give a profit, on average, turns an agricultural loss of 7.3 billion USD yr$^{-1}$ into a profit of 16.9 billion USD yr$^{-1}$. Large tracts of land are left fallow, either permanently (almost 70% of the baseline cropped area, figure 2(a)) or seasonally, that is, during the rabi season in years of below-average monsoon rainfall (at least once in 10 years on another 10% of the cropped area). The area under irrigation is halved, reducing irrigation amounts by approximately two-thirds to just over 50 billion m$^3$ yr$^{-1}$, although with strong regional variation (figure 2(c)-GF1); the marginal value of irrigation water is higher for crops such as pulses and oil crops grown in the western part of the basin than for the rice dominated cropping systems further downstream towards India’s Bihar and West Bengal states, and Bangladesh. The average number of people that can be fed is strongly reduced under this scenario, with nutrition for less than 200 million people.

To achieve maximum nutritional yield, the storage of water in local reservoirs, such as farm ponds and shallow groundwater, is maximised at the expense of irrigation from the canal system. Small reductions in irrigation mainly in the west of the basin, mainly in India’s Rajasthan province, benefit limited expansion of irrigation downstream. There is
Figure 2. Dominant land use (a), cropping intensity (b) and fraction irrigated (c) at present (year 2010, 'baseline'), and dominant land use, change in cropping intensity and change in fraction irrigated compared to 'baseline', for each individual goal function (GF), with 'nutrition' as a secondary goal function to keep each solution as close to the 'baseline' as possible. The k(r) in the crop type name stands for the Indian crop season name 'kharif' ('rabi'). Cells in which less than 10% is used for agricultural purposes, mainly the mountain regions of the Himalayas, are masked in grey.

limited opportunity, however, according to our simulations to expand food production under current land use and levels of technological progress. The marginal benefit of feeding an additional 2 million people compared to the baseline, leads to the use of large amounts of shallow groundwater and significantly higher costs of water application (table 2).

The yield from hydropower (GF3) varies between 7100 GWh per year when not prioritised and three times as much (21 748 GWh) when optimised. This higher value represents a basin-wide capacity factor (the actual amount of energy generated versus the potential) of 29% at the lower end of the international standard [49] and lower than the reported capacity factor of 42% of new hydropower plants in India [56]. Runoff in the basin is highly seasonal, and hydropower is used to meet peak demand, complementing conventional fossil fuel power plants. Moreover,
many existing dams have multiple purposes and are designed for irrigation releases and flood moderation. When prioritising hydropower, the existing land use pattern tailored to maximum nutrition can largely be maintained, but surface irrigation is strongly reduced.

Similarly, maximising environmental flows downstream has a strong effect on surface water irrigation, while leaving groundwater irrigation, land use, and cropping intensity largely intact. An environmental flow of $1982 \text{ m}^3\text{s}^{-1}$ (GF4) could be maintained in all optimisations, while the maximum minimum amount of runoff that could be achieved was $2870 \text{ m}^3\text{s}^{-1}$ (table 2).

### 3.2. Trade-offs between SDGs

Figure 3 shows the interconnectedness between SDGs, with each line representing one Pareto optimal solution, while crossing lines indicating trade-offs and horizontal lines following the upper part of the graph suggesting synergies. Crossing lines between profit and nutrition in all solutions confirms a particularly strong trade-off; with high positive profit, nutrition is more than halved. If nutrition is maintained at the current level, agriculture cannot be profitable under current management practices. Moreover, high energy use for pumping tends to be associated with high nutrition (production) and low profit, and vice versa. Avoiding energy use for pumping groundwater altogether, thereby also minimising groundwater depletion, reduces nutrition for at least 96 million people, a 20% reduction (line ‘a’).

Without access to groundwater, these nutrition levels are to be met by surface water irrigation from regions where agriculture is less profitable, and by rainfed agriculture which has lower yields.

Trade-offs between the other indicators are weak. Downstream environmental flow is reduced by a maximum of 25% under optimum hydropower yield, although at $2117 \text{ m}^3\text{s}^{-1}$, it remains above the required minimum threshold. Hydropower yield is largely unaffected by other goals, indicating synergies rather than trade-offs, such as between Nepal’s hydropower production and irrigation in northern India [8], with the timing of melt, onset of monsoon rains, peak demand for energy during the hot summer, and irrigation requirements for rice nurseries and transplanting largely coinciding. Most existing dams the Brahmaputra River basin, in China, Bhutan and east India, have only small storage reservoirs, and while these might have an environmental impact locally, they do not affect downstream agriculture profitability of production much.

### 3.3. Economic versus operating costs of production

The strongest trade-off, between profit and nutrition, shows the typical curve of diminishing returns (figure 4). Growing crops such as rice in the downstream part of the basin is not economically viable in the long run, given the current cost of production and price levels. To understand why farmers still plant these crops, and why current land use and irrigation resemble nutrition rather than profit maximisation,
we compared the trade-off based on the total economic costs (C2) with a more limited operating cost estimate (A2) which excludes the imputed value of family labour and the rental value of owned land (see Methods). Under A2 costing, the trade-off is much less severe and agriculture appears profitable, with a minimum profit of over 35 billion USD yr⁻¹, or an average of 270 USD ha⁻¹ yr⁻¹. Even when profit is maximised, the number of people that can be fed remains above 500 million; most crops return modest profits on an operating cost basis. Farmers’ business income is positive, and direct expenses for fertilisers, pesticides, seeds, water, and machinery are covered. However, their own time input, that of family members, and the value of their land are not.

Potentially higher energy prices, which mainly affect groundwater-supported production, were evaluated through a sensitivity analysis of the irrigation water costs (figure 4). A higher volumetric cost of irrigation water marginally increases the trade-off between profit and nutrition. The cost of irrigation is just 5% of the total input costs on irrigated fields in C2 costing, at 0.02 USD m⁻³. At maximum production, the net profit, which is already negative, is further reduced by ~30% when irrigation costs double. Substitution of groundwater with cheaper surface water buffers the impact of higher volumetric costs, especially at low nutrition and water demand levels, but this shift in the source of irrigation is never more than 5% of the amount of groundwater irrigation. In the dry season, when most groundwater extraction takes place, the availability of surface water is limited. The impact on the trade-off of higher cost of irrigation under A2 costing is negligible. Still, it does represent an important input cost (8% of total input costs at 0.02 USD m⁻³ and almost 15%, at 0.04 USD m⁻³). This illustrates a farmer’s dilemma: while volumetric costs are small compared to the gross profit irrigation water generates, and a farmer will likely always pay to secure it, he would prefer not to, given its percentage of operating costs and the small net profit margins that remain, if any, when total economic costs are considered.

3.4. A compromise

Generally, there is no single optimal solution when multiple objectives are combined. However, from the Pareto optimal solutions we generated, an attractive compromise combines at least a positive economic agricultural net profit (at 1 billion USD yr⁻¹, with gross profit remaining above 35 billion USD yr⁻¹, or approximately 270 USD ha⁻¹) and high nutrition levels sufficient for almost 500 million people while generating a large amount of hydropower and maintaining river flow downstream (line ‘b’ in figure 3). The existing land use pattern is largely retained (figure 5(a)), but different from the baseline scenario, the most unprofitable land use is fully taken out of production and the intensity of land use is reduced, with land left fallow in years of less rainfall, especially in the central and drier southwestern part of the Ganges Basin (figure 5(b)). The largest permanent reduction in land use is found in the Bangladesh delta and northeast India, where a double rice crop rotation returns mostly negative margins. The increase in the fraction of land that is irrigated (figure 5(d)) primarily mirrors this change in cropping intensity rather than reflecting an increase in irrigation volume.

One indicator on which this solution continues to score low is energy use for groundwater pumping, as significant amounts of groundwater are needed to maintain production. The northwestern part of the Ganges Basin in particular is a hotspot of groundwater stress [45]. To test the dependence on groundwater, we further constrained the maximum area under groundwater irrigation through deep tube wells in the two most western states of the Ganges Basin, Haryana and Rajasthan, by 50%. Food production can be maintained, but at a cost. The loss of highly productive irrigated production during the dry season can only be compensated by less profitable production elsewhere in the basin, reducing the overall economic profit margin from 1 billion to just over 100 million USD yr⁻¹.
4. Discussion

4.1. Transition
We characterised the most important SDG trade-offs within the WEFE nexus in the Ganges–Brahmaputra–Meghna river basin system. The trade-off between agricultural profitability and total production is strong, when taking into account total economic costs, and currently tilted toward the latter. South Asian countries have prioritised food production and self sufficiency [23], with input subsidies reducing operational costs and ad hoc support, such as increased access to credits in times of elections [57] or loan waivers [32], providing partial compensation. The continued low profitability risks discouraging farmers from engaging in agriculture [25, 32]. Yet, a large part of the population remains trapped in farming, as off-farm alternatives in rural areas remain limited, and low-paid jobs in cities only offer tentative security as the COVID lockdown exposed.

A compromise was identified, but with significant energy use by irrigated agriculture not easily constrained. A transition to solar-powered irrigation could reduce both the cost of energy use and fossil fuel emissions, but safeguards against overextraction of groundwater remain needed. Selling excess solar energy to the electricity grid [38], powering filtration systems to provide clean drinking water [55] or scheduling irrigation around peak demand by urban areas [55] thereby absorbing fluctuations in renewable energy in the grid, are some of the promising solutions to delink (cheap) energy supply from water use. Groundwater extraction could also benefit recharge and retention in regions with a highly seasonal rainfall pattern. A more detailed analyses using location specific data on groundwater levels can help identify promising, cost-effective application.

4.2. Feedbacks
Feedback and innovation may buffer some trade-offs, especially between production and profitability. A drastic reduction in domestic crop production would affect supply and likely raise prices, depending on the import response, which, in turn, would increase farm profitability. Various water-saving technologies or agronomic practices could lead to a reallocation of scarce resources [59, 60], reduce costs, and increase profit, although their financial feasibility [62, 63] and overall effectiveness has been questioned [62, 63]. While expansion of area has ceased to be a source of growth of agricultural output in most parts of India [34], further closing the crop yield gap through improved crop varieties, better management and crop rotations could improve profitability by reducing fixed costs per unit produced; in various parts of Bangladesh triple cropping of rice is nowadays practiced [64].

4.3. Climate change
While climate change projections suggest more run-off in these basins, at least in the near future [65],
inter-annual and intra-annual variability in precipitation and runoff may increase, with the buffering capacity of glaciers gradually diminishing [66]. We simulated seasonal cropping choices by farmers as a coping strategy to make the best use of varying water resources. A better understanding of the future feasibility of such coping as an adaptation strategy under climate change and changing demands for food and water is needed.

Downstream demands from countries such as Bangladesh have set limits on the amount of water that can be extracted upstream. The international water treaty between India and Bangladesh, allocating flows of the Ganges entering Bangladesh, is expiring in 2026. Our results suggest that there is room to satisfy the increased environmental flows toward both the Hooghly diversion and the Ganges–Brahmaputra delta. However, this should be tested over longer periods, including years with more extreme events.

### 4.4. SDGs and the nexus

In recent years, the nexus concept has become a dominant framework for assessing resource use, scarcity, and interconnectedness. SDGs prioritise global ambition levels, while planetary boundaries set thresholds that should not be exceeded [1, 67]. Our analysis addressed a limited set of SDG goals and targets and it has been shown that selection of indicators can lead to a substantially different relative evaluations of the SDGs [68]. Still, a multi-objective optimisation approach at the basin scale, such as that presented here, helps to integrate these different frameworks. Ideally, this supports policy makers in their decisions by highlighting the trade-offs and synergies that matter, thereby focusing on coordination between sectors and stakeholders and targeting effort and resources. With limited resources, multiple stakes, and changing boundary conditions, determining the best compromise is essential for effective river basin management.

### Data availability statement

The data generated in this study (i.e. input and output of model simulations) are available online open access in a figshare archive [https://doi.org/10.6084/m9.figshare.19142654.v1](https://doi.org/10.6084/m9.figshare.19142654.v1). The code for the WaterWise model is available at [https://git.wur.nl/christian.side rius/waterwise-hydro-economic-model](https://git.wur.nl/christian.siderius/waterwise-hydro-economic-model). The code for the LPJmL model is available at [https://github.com/PIK-LPJmL/LPJmL](https://github.com/PIK-LPJmL/LPJmL).

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### Author contributions

C S, P V W and H B designed the study. H B provided the hydrology-crop model output, while P V W improved the optimization model, with contributions from C S, C S and P V W analysed the data and prepared the figures. C S wrote the article with major contributions from both coauthors.

### Conflict of interest

The authors declare no conflict of interest.

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