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Assessing policy options for sustainable water use in India's cereal production system

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Abstract

In India, the production of rice and wheat account for more than 80% of its total agricultural water use. As farming is highly dependent on water availability, rapidly receding water levels require urgent measures to manage withdrawals. We assess policy instruments that can reduce pressures on water resources, while at the same time limiting adverse impacts on water-intensive cereal production systems, land-use changes and economic welfare. To this end, we use a dynamic and integrated partial equilibrium model of agricultural production and its impact on the environment to reflect two options: an increase in energy costs for irrigation water (price-related effects), and alternatively, physical quotas on water withdrawals (quantity-related effects). We conclude that it is possible to increase energy prices for agriculture with minimal impacts on agricultural production, agricultural prices, and trade in cereal crops, and moderately reduce water withdrawals by 2050. We find that the intermediate effects of pricing policies are negative for all indicators as compared to quota policies. However, by 2050, both policies yield similar outcomes for all indicators. Our results offer insights into ways in which these policies drive different mechanisms and trade-offs on important agro-economic indicators, and they offer the choice for water conservation policy decision-making based on other critical factors such as implementation costs.

1. Introduction

Agricultural production needs to expand to meet growing food demands (Rockström *et al* 2009, Foley *et al* 2011). This is true particularly in low and middle-income countries where yields remain low (Bodirsky *et al* 2020, Timothy *et al* 2021) and where the majority of freshwater is used in food production (Aeschbach-Hertig and Gleeson 2012, FAO 2019). Globally, agricultural withdrawals account for more than 70% of water withdrawals (Faurès *et al* 2002), mostly for rice and wheat production (Ringler and Zhu 2015, Dalin *et al* 2017). In the case of India, total irrigated area nearly tripled to 33 million ha (Mha) between 1970 and 1999 and increased further to 68.6 Mha in 2020–21 (Zaisheng *et al* 2007, MoAFW 2021). It continues to rise, thereby putting pressure on the water resources in the country (figure S1 in supplementary material (SM)). India stands out in the food production-water consumption nexus. It withdraws and consumes the largest volume of freshwater resources globally, mostly for the production of basic staple crops of rice and wheat that account for more than 80% of total agricultural water withdrawals in India (Jain *et al* 2017, Kayatz *et al* 2019). Irrigated area development for these staple crops was a key component of the Green Revolution that started in the 1960s (Shah 1993, Badiani and Jessoe 2019). New high-yielding varieties were developed during this period, which, together with irrigation and adequate fertilizer access, leading to the world's largest contiguous rice-wheat system (Devineni *et al* 2022). The system was further incentivized by the provision of cheap, and sometimes free, electricity to pump water out of the ground. As a result of this strategy, crop yields increased while food prices and food import dependency declined (Scott and Shah 2004, Briscoe and Malik 2006, Badiani *et al* 2012). However, with existing and future socio-economic challenges and rapid groundwater table declines, a need for an approach focused on efficient irrigation practices and sustainable management of water is increasingly being considered inevitable (Jain *et al* 2021, Rosa 2022).

Two strategies to reduce agricultural water depletion are in vogue, typically: irrigation water pricing that reflects the marginal cost of water withdrawals, or a quota system that limits water withdrawals in agriculture. There is evidence that water prices reflecting it's scarcity value can help reduce wastage (Dinar 1998) and have been successfully applied in several countries to manage demand (Shah 1993, Saleth 1997). Differential water tariffs for consumer groups based on farm sizes have been found to improve irrigation efficiency and decreases in irrigation based withdrawals in the Duero valley in Spain (Gómez-Limón and Riesgo 2004). Similar results have been observed by Kumar *et al* (2013) for three large sub-national regions in India. However, most studies caution that for irrigation water use to decline, the water price would have to be set at a level that nudges farmers out of that specific crop production (de Fraiture and Perry 2007, Han and Zhao 2007, Molle *et al* 2008).

Alternatively, water withdrawal quotas or restrictions can positively impact the sustainability of irrigated agriculture. In developing countries, where small farms dominate, the physical estimation of water withdrawals can be done based on the time and duration of supply, and flow levels in the canal. An example of which is the *warabandi* system in Pakistan (Bandaragoda 1998). Similarly, bulk allocation at the level of water use associations has also enabled conservation in countries like Sri Lanka (De S. Hewavisenthi 1997), Turkey (Cakmak *et al* 2004), Mexico (Kloezen 2002) and Israel (Kislev 2003). Physical restrictions on water use through bulk allocation are relatively easier to implement, have low transaction costs in some cases, and are more equitable compared to water pricing, which may disincentivize efficient farmers (Molle 2009).

Both of these options have received some attention in the agricultural water policy context in India (Humphreys *et al* 2010, Patel 2016, Chaudhuri and Roy 2019). Studies have assessed the role of irrigation in groundwater depletion (Jain *et al* 2017, Zaveri and Lobell 2019, Xie *et al* 2020), and of changes in energy prices on crop choices in north-west India (Bhattarai *et al* 2021, Mitra *et al* 2022, Singh *et al* 2022). Additionally, assessments of water withdrawal restrictions for environmental protection in India have also been undertaken (Baghel *et al* 2018, Jha *et al* 2022). However, the long-term consequences of these policies on agricultural production, irrigated areas, output prices and trade patterns remain unknown. This study aims to fill this gap by providing an assessment of agroeconomic implications of regulatory water policies and their effectiveness in the future at the national level. We use a spatially explicit global land use model, the model of agricultural production and its impact on the environment (MAgPIE) which has India as a separate region in focus (Lotze-campen *et al* 2008, Dietrich *et al* 2019). The MAgPIE model is an integrated land-use modelling framework that combines bio-geophysical properties of land with agroeconomic decision making. It allows to evaluate the impact of agricultural policies on future food prices, energy use and land use trajectories, under the specified socio-economic and biophysical constraints. The model optimizes future land use patterns by following a cost minimization approach to meet global food, material and bioenergy demand with population, economic growth, and climate change scenarios as exogenous drivers. To the best of our knowledge, no other study has looked at this question with a comprehensive framework that accounts for both economic and biophysical constraints at the national level. Details of important parameters, elasticities and assumptions are presented in appendix 1a in SM.

The model has previously been used to identify sustainable transformation pathways for India specifically (Jha *et al* 2022). The model has also been used to analyse sustainable agricultural water withdrawals and land use at the global scale (Bonsch *et al* 2015) as well as synergies and trade-offs in water-land-food-climate nexus globally (Doelman *et al* 2022). In this study, we use the model to analyse the impact of our water policy scenarios on key environmental and economic indicators, such as agricultural water withdrawals, irrigated cropland expansion, changes in agricultural prices of major crops and producer profits, cereal crop production, particularly rice and wheat, and the implications on India's cereal trade balance by 2050.

2. Methodology and scenario description

MAgPIE is a global recursive dynamic partial equilibrium model used to assess land-use allocation and competition for resources like land and water, and the associated consequences for sustainable development under future scenarios of rising food, energy and material demand, climate change impacts, and land-related greenhouse gas mitigation policies (Dietrich *et al* 2014, Dietrich *et al* 2019). The model simulates agricultural demand, crop production, land-use patterns and water withdrawals for irrigation under socio-economic and environmental constraints and projects land-use change in 5 year time-steps (every five years) until the year 2050. It uses biophysical inputs including crop productivity and water availability at a spatial resolution of $0.5° \times 0.5°$, which are further aggregated to clustered units (200 in this analysis) for optimization in the model. These are provided by the Lund-Potsdam-Jena dynamic global vegetation and water balance model with managed Land (LPJmL) for every grid cell (Bondeau *et al* 2007, Schaphoff *et al* 2018, von Bloh *et al* 2018). Figure S1a in the SM demonstrates the input and output structure of MAgPIE. For computational reasons, these inputs are aggregated into spatial clusters characterized by similar biophysical conditions.

2.1. Water representation in MAgPIE

Water availability in the model is calculated from spatially explicit runoff and discharge provided by LPJmL. To obtain yearly water availability in the growing period at the level of spatial clusters, basin runoff is allocated among the grid cells of each river basin using monthly discharge as allocation weight. The available water for every grid cell in every month that is part of the growing period is then aggregated to cluster level for every year. Water use in MAgPIE differentiates between agricultural and non-agricultural withdrawals. Non-agricultural water requirements are provided as exogenous scenario from WATERGAP (Müller Schmied *et al* 2021) and are prioritized over agricultural withdrawals, thereby constraining water withdrawals for irrigation. Water withdrawals for agricultural production are determined endogenously considering livestock water demand and water requirements for each crop in their growing period. Overall water demand is constrained by total water as per equation in appendix 2 in SM. Changes in water withdrawals in one time-step do not affect water availability in the next time step in our model, as water availability is exogenous. The model does not account for fossil groundwater stored in deep aquifers for which recharge rates depend on several external factors such as climate change (Fu *et al* 2019). To assess the effect of irrigation water pricing, we explicitly add costs of energy used for pumping irrigation water (USD per cubic meter) for India in MAgPIE. This influences the model's cost optimization, where other input costs of production, such as fertilizers and capital, are also included. To simulate scenarios for India, we vary prices between scenarios. Physical water restrictions are implemented through restricting water withdrawals to a specific percentage of available water.

2.2. Scenario description

For the analysis of water policies for India, we create four different scenarios following below guidelines and assumptions: two scenarios each for price- and quantity-related targets (table 1) to compare with a business-as-usual (BAU) scenario. Irrigation water prices or pumping costs in BAU are based on values found in the literature on historical and present prices for electricity supply for agricultural use. In India, energy prices for agriculture are charged at flat rates, in per kilowatt hour (kWh), varying in values at the sub-national level. To compare with global values, we transform these values into volumetric pricing by using information on the average horsepower of pumps used for drawing water, their drawing capacity and number of hours of irrigation applied (details in appendix 3 in SM). Information on trends in energy prices in India since 2007–08 to 2011–12 (figure S3 in SM) from the Power Finance Corporation Ltd (2015) are used to convert prices in Indian rupees (INR) per kWh to INR per cubic meter and further to USD as per 2005 market exchange rate using the methodology and assumptions in table S1 and S2 in SM. For the BAU scenario, pumping costs for irrigation in India take the values of 0.005 USD per cubic meter ($\sim$ INR 4.04 per kWh). Our values on the cost of pumping irrigation water in India are equivalent to the average energy prices as reported by the Power Finance Corporation Ltd (2015), values used by Bhattarai *et al* (2021) in the medium energy price scenario and global values reported by Cornish *et al* (2004). For the price-related policy scenarios, we create two scenarios: In the first (low-price scenario), current prices are doubled, to meet the highest energy price charged by a state in India; in the second scenario (high-price scenario), a significant reduction in water withdrawals is targeted and prices are increased by a factor of four.

For quantity-related scenarios, we impose physical restrictions in water withdrawals. To be directly comparable with the price scenarios, we create two quota scenarios: first, a low-restriction scenario in which 40% of available water in the growing period is reserved for the environment with the remaining available for human withdrawals (agricultural and other human purposes). This corresponds to a 16% reduction in water withdrawals for agriculture after optimization by 2050 and is therefore similar to the reduction achieved by the low-price scenario in 2050. Similarly, to compare equivalent water withdrawals as the high-price scenario, we create a high restriction scenario in which 60% of available water is reserved, thereby effectively reducing water withdrawals for agriculture by 44% in 2050. Both these scenarios allow us to compare directly with the price-related effects as they are both projected to reach equivalent reduction targets in agricultural water withdrawals by 2050.

All policies take action after 2020 in the model. All scenarios are parameterized according to the Shared Socio-economic Pathways (SSP) specification with the middle-of-the-road trajectory for the future

Table 1. Description of model setup and scenario design for the analysis.

Policy tool	Scenario description	Pumping cost (USD per meter cube)	Physical water availability setting	Scenario name
BAU	No quota implemented, Pumping costs (∼INR 4 per kWh)	0.005	No policy	Business as usual (BAU)
Price-related effect I	Pumping cost prices equivalent to highest price of energy across all states in India from 2007–2013 (∼INR 8 per kWh)	0.01	No policy	Low-price
Price-related effect II	Quadrupling of India prices (∼INR 16 per kWh)	0.02	No policy	High-price
Quantity-related effect I	Reserves **40%** of available water for conservation, remaining water is available for human uses (agricultural and non-agricultural)	0.005	Quota policy I	Low-restriction
Quantity-related effect II	Reserves **60%** of available water for conservation, remaining water is available for human uses (agricultural and non-agricultural)	0.005	Quota policy II	High-restriction

(SSP2) (O'Neill *et al* 2014). The BAU scenario represents a future based on current policies and historical trends, with a considerable increase in population and food demand (details of assumptions under SSP2 scenario presented in appendix 1c in SM).

3. Results

3.1. Agricultural water withdrawals

Changes in water withdrawals and water withdrawals per sector in India are presented in figure 1. In the BAU scenario, we observe that water withdrawals for agriculture decrease by approximately 8% between 2020 and, 2050, despite only a small decrease in water availability for agriculture (due to climate change). This reduction is a result of the increase in withdrawals for other non-agricultural sources (domestic, manufacturing and electricity) and various other factors including climate change impacts. In comparison, all quantity and price scenarios show a greater reduction of water withdrawals for agricultural purposes by 2050. This happens because as water resources become scarce (through either price policy or quantity restrictions), the returns to irrigated cultivation are less profitable across all policy scenarios.

As prescribed in the scenario settings, both price and quantity related scenarios cause approximately the same reduction in water withdrawals by 2050 (19% and 16% for low-price and low-restriction and, 44% for both high-price and high-restriction scenarios). The actual reduction might even be higher due to inherited uncertainties in modelling particularly with underestimation in validation against observed data (figure S4 in SM). In 2030, a greater reduction in water use is observed in both price related scenarios, whereas it stabilizes by 2050 corresponding to water withdrawals in the quantity related scenarios by 2050. These reductions in water withdrawals can be explained by increasing demand for water by the manufacturing sector. However, the trajectories of impacts are different (figure S4 in SM). We find that effects of both price and quota policies take place after 2020, but price adjustments are dynamic, whereas the quota restrictions are uniform across the time periods until 2050. Since quantity scenarios restrict a constant share of water availability for agricultural use, they change only slightly over the years based on water availability, after the initial reduction. The dynamics in the price scenarios on the other hand are explained by investments and interest rates, where increasing costs reduce the incentive for water withdrawals. Adjustments within production systems occur due to changing physical availability of water in every timestep as well as the cost to use it. Due to the increased price for irrigation, crop production is shifted towards rainfed production. After the initial shock, the withdrawals for agricultural purposes

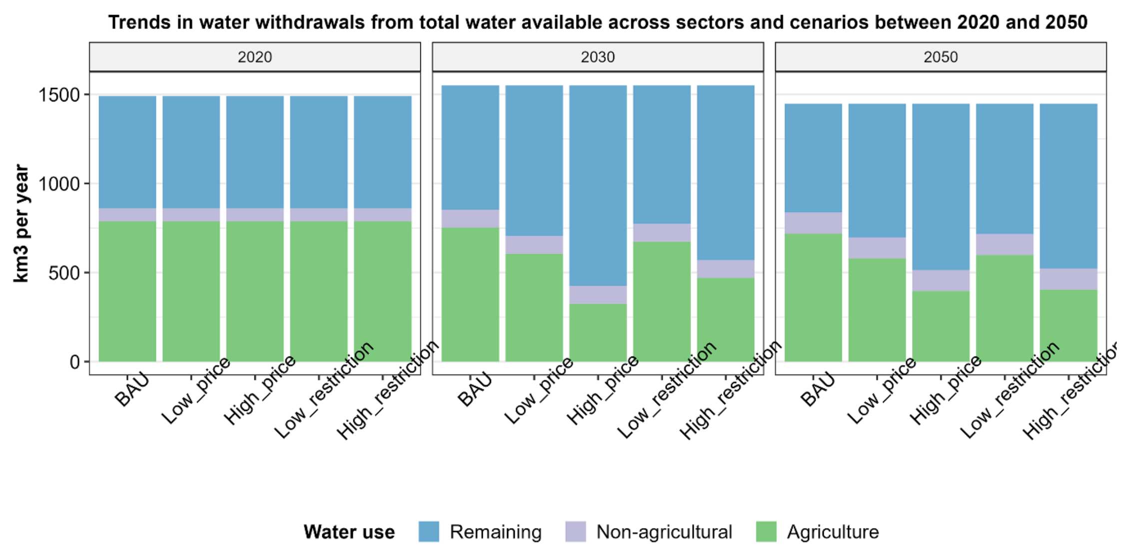

Figure 1. Changes in agricultural water withdrawals across sectors and scenarios from 2020 to 2050 for India. The height of each bar represents total water availability over the years and withdrawals for agricultural and non-agricultural withdrawals are presented. These values offer insights into the total reduction in water withdrawals that can be obtained with equivalent reductions observed in the low-price, low-restriction and high-price, high-restriction scenarios respectively, by 2050.

remain stable until 2050 in the low-price scenario. It offers a plausible scenario to manage stable water withdrawals for agricultural purposes with increased state revenue from the increase in energy prices by a small extent (0.1 USD per cubic meter), while retaining agricultural profits.

Changes in water withdrawals have a direct effect on irrigated croplands. In the BAU, we observe an increasing trend in irrigated croplands as a share of total croplands (83% in 2050 as compared to 66% in 2002). In comparison, we observe that this share declines in all scenarios except the low-restriction scenario in 2030 (figure 2). By 2050, all scenarios report lower shares of irrigated cropland. By 2050, the share of irrigated croplands reduces most for the high-price scenario (29%), followed by the low-price and high-restriction scenarios that each reduce by 24% and 23% respectively.

3.2. Cereal production

Changing water withdrawals across scenarios have anticipated effects on overall agricultural production as well as irrigated croplands. In the BAU scenario cereal production increases by 59% between 2020 and 2050. Production also increases overall in other scenarios, but the rate of growth is slower than in BAU. We observe a small reduction in the production of cereal crops in the low-price scenario (6% less than BAU in 2030 and 4% in 2050). In the high-price scenario, cereal production is 22% lower than BAU in 2030 and 9% in 2050 (figure 3). For the quantity scenarios, cereal production is 2% less than BAU in 2030 in the low-restriction scenario and 9% in 2050, whereas it is 15% and 9% less than BAU in 2030 and 2050 for the high-restriction scenario. Overall cereal production is minimally affected in the low-price scenario by 2050, supporting our observation that this scenario brings less distortions in overall production patterns, while at the same time reducing agricultural water withdrawals for agriculture in India to some extent. For individual crops, we observe that both low-price and low-restriction scenarios bring similar effects in the production of wheat, whereas both high-price and high-restriction scenarios cause greater reductions in the production of rice. Wheat production faces a greater decline (26% less than BAU in 2030) as compared to rice (9%) in the high-price scenario whereas rice production observes a decrease in production by 19% in both high-price and high-restriction scenarios. For both crops, the low-restriction scenario is more favourable by causing least reductions in production quantities and areas, thereby suggesting that a regulatory policy such as the low-price or low-restriction scenarios may cause only small adverse impacts on production outcomes of key cereal crops in India.

3.3. Agricultural prices and profits

All our scenarios create impacts on agricultural commodity prices because of underlying changes in direct (price related effects) and indirect (quantity related effects) costs of production. In figure 4, we report the results of Agricultural Commodity Price Index, as an aggregate measure of primary agricultural commodity prices, as well as the prices of rice and wheat, the two main crops, with validation data presented in figure S5 in SM. Prices in MAgPIE are reflective of long-term scarcity as calculated by marginals of production constraints. Higher price values in our results therefore imply an increased

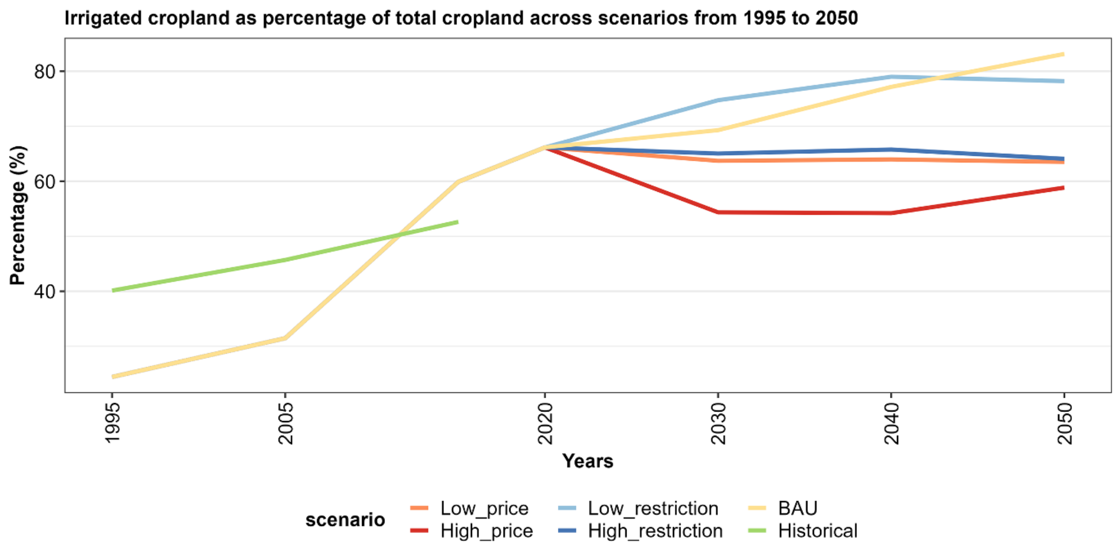

Figure 2. Changes in irrigated cropland as a percentage of total cropland across scenarios from 1995 to 2050 and including validation data sourced from the database of the Ministry of Agriculture, India. As compared to the BAU, the share of irrigated cropland increases in the low-restriction scenario in the initial timesteps, to reduce marginally by 2050. In all the other scenarios, a reduction in the share of irrigated croplands is observed, with the maximum change in high-price scenario, followed by low-price and high-restriction scenarios respectively.

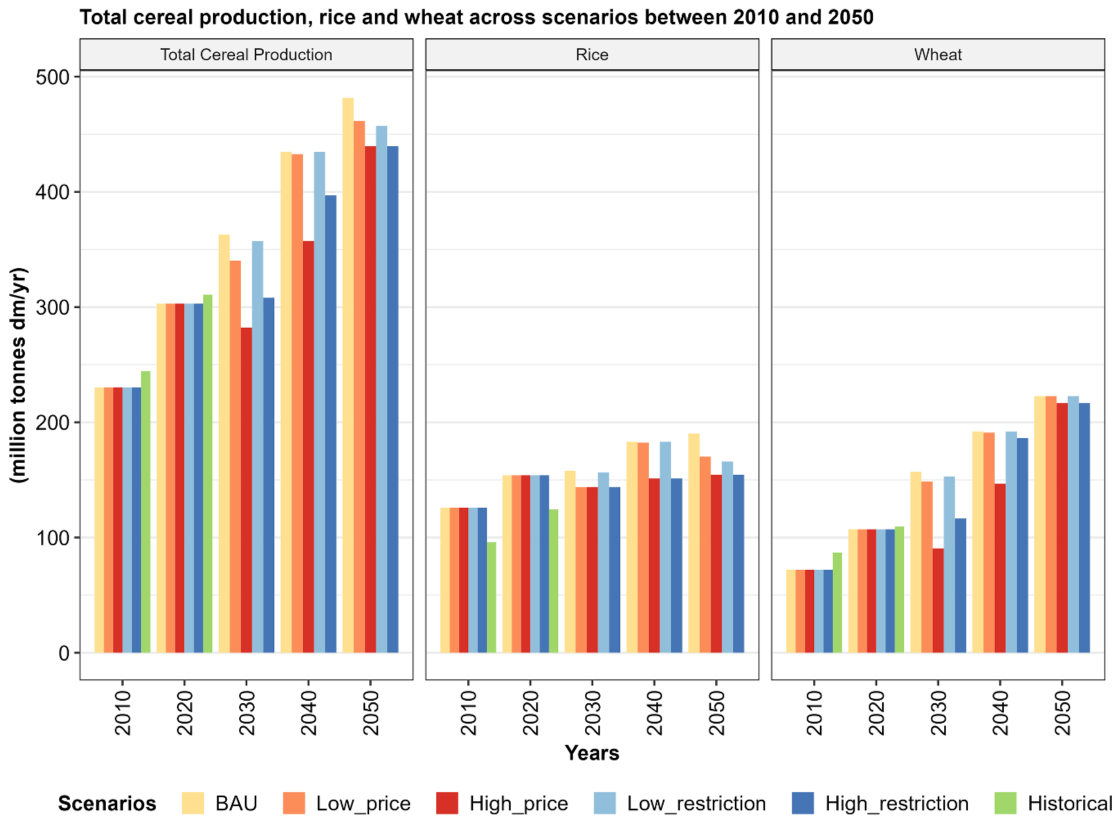

Figure 3. Changes in production of total cereal crops, rice and wheat production across scenarios from 2005 to 2050 and historical data sources from the Ministry of Agriculture, India, in million tonnes dry matter per year (Mt dm/yr). The lines represent actual values of production across scenarios. Wheat production is more affected by high-price scenario whereas rice production is affected equally by both high-price and high-restriction scenarios. Overall, the high-price scenario brings greater declines in total cereal production, followed by the high-restriction scenario.

scarcity of the commodity. For aggregated agricultural commodities, we observe higher prices under all scenarios as compared to BAU, where prices decline by 11% by 2050 compared to 2020. Large intermediate shocks of rising prices are felt in the high-price scenario for all food crops, particularly

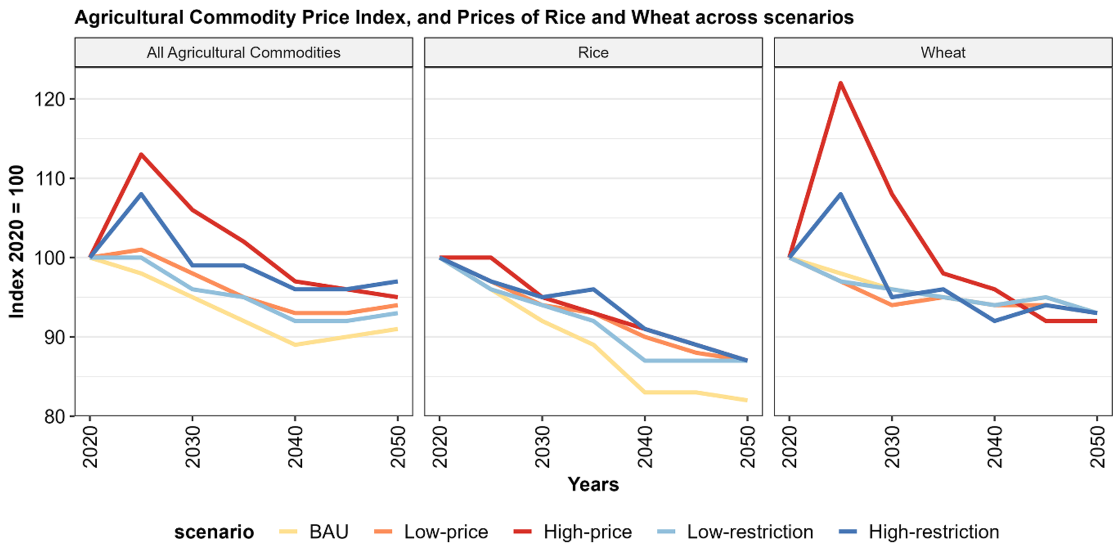

Figure 4. Changes in the Agricultural Commodity Price Index as well as commodity prices of rice and wheat across scenarios compared to 2020. Values are indexed to the year 2020. All scenarios report an increase in prices as compared to 2020, with a sharp rise in 2030 for the high-price scenario, particularly for wheat. By 2050, all scenarios report lower prices than 2020, but higher than BAU, except high-price scenario for wheat.

wheat, but by 2050, this scenario reports lowest prices for wheat. Whereas for rice, all scenarios converge to values higher than BAU by 2050. This indicates that any increase in the costs of irrigation water will influence the prices of food crops in the short-term, particularly wheat, but may not be very different from the BAU by 2050. The increase in prices can be explained by investments in technological intensification that are needed to maintain agricultural productivity in 2025 and that payout in the future (figure S6 in SM). To assess the impact on producers of agricultural products, we calculate profits from production by multiplying total production of the commodity with resulting producer prices and subtracting the total costs of production of the commodity for every time step. Given the limitations in projecting long term commodity prices (appendix 1, section B and appendix 1b in SM), evaluated profits from agricultural production in the model should be taken as an indicator to demonstrate the direction of potential economic impacts of policy scenarios on an average agricultural producer. We find that there are limited adverse consequences for producers with the implementation of these policies. In 2030, all scenarios report higher producer profits as compared to the BAU and by 2050, profit is highest in the high-restriction scenario (3% higher than BAU) (figure S7 in SM). Although these values are small, they highlight the possibility of implementing water governance policy measures with limited adverse consequences on agricultural producers and consumers.

3.4. Agricultural trade

Domestic policies on crop production also have implications on a country's ability to maintain food self-sufficiency, defined as the ratio of total domestic production over total domestic demand. We evaluate food self-sufficiency by comparing trade patterns of cereal crops (validation data presented in figure S8 in SM). In the BAU scenario, net exports are increasing by 63% by 2050. In comparison, our scenarios report reductions in net exports of cereal crops, with the largest reduction observed in the case of high-price followed by the high-restriction scenarios in 2030 where India becomes a net importer in the short term (figure 5). This trend continues until 2050 where net exports remain less than in the BAU in all scenarios, with least reductions observed in the low-price and low-restriction scenarios. However, in 2050, India returns to being a net exporter of cereal crops across all the scenarios, but with reduced exports compared to the BAU. This happens because production systems stabilize as a result of technological intensification, and some recovery in exports is made, thereby reducing the overall adverse impacts by 2050. As a result, by 2050, all scenarios report lesser exports, but India's trade-balance is restored after the policy shock. India's self-sufficiency for major crops such as rice declines in our scenarios, as compared to BAU in 2050 threatening food security to some extent (figure S9 in SM). This is a significant trade-off of implementing regulatory policies for water withdrawals in India's agricultural production systems.

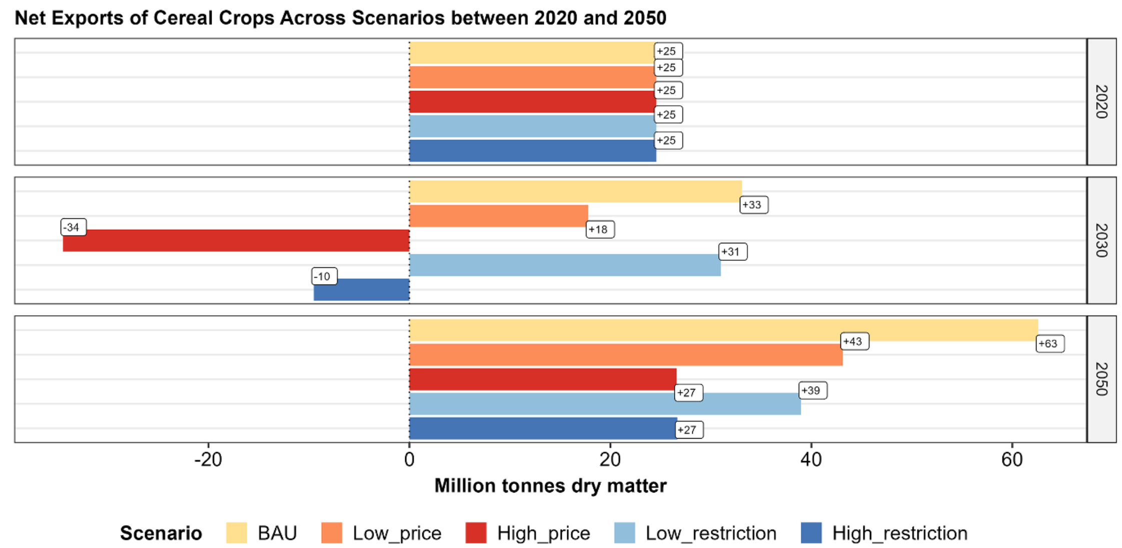

Figure 5. Net exports of cereal crops across scenarios between 2020 and 2050. Net export values are generated by subtracting total imports from total exports. A negative value indicates a country is net importer of cereal crops to meet domestic food demand whereas a positive sign indicates an increase in overall exports because of cheaper domestic production of cereal crops.

4. Discussion

Our results draw attention to the potential impacts of two alternative policies to manage the use of limited water resources for agricultural production in India, aligning with the necessary goal of maintaining food security and self-sufficiency in the agricultural sector in the long-term. We review governance measures and their trade-offs on important outcome indicators (agricultural production, producer prices and trade balances). We conclude that polices which imply restrictions on physical water extraction as well as increases in energy prices for irrigation bring differential impacts in the intermediate term, on agricultural production, similar to a simulation study of similar policies in the USA by Graham *et al* (2021). This is a first assessment of both price- and quantity-related effects of water governance policies in India for the future. Our results offer insights into the different mechanisms that these policies drive, and trade-offs on important agroeconomic indicators. Our scenario design was motivated to assess the trajectories of different policy tools that were designed to arrive at the same level (40%) of water withdrawals reduction in the future. Using these tools with a future goal, we can compare their transition pathways over time, and we observe the interplay between different factors of production and other exogenous factors such as trade that affect model outcomes. Moreover, our scenarios of 'low_price' and 'low_restriction' demonstrate that they result in similar levels of water withdrawals in modelled time steps. Despite that, we observe differences in outcome indicators—agricultural production, prices, and trade over time, reflecting the actual differences in policy implementation.

Our scenarios on prices suggest that by implementing an average price of 0.1 USD per m^3 (equivalent to INR 11.71 per kWh) it may be possible to minimize the negative impacts on agricultural production and agricultural prices while achieving a reduction of water withdrawals to 40% of available water by 2050. The scenario on low-prices particularly demonstrates that profits from production are higher even with an increase in input costs. This is similar to a study in three states in India by Kumar *et al* (2013), in Algeria by Oulmane *et al* (2019), and Shiferaw *et al* (2003) who reported that water prices can be introduced without having significant negative impacts on the profitability of smallholder farmers. This scenario presents a suitable and feasible option that enables cost-saving in energy subsidies, with least impacts on agricultural production, prices and trade balance. Average rates of 1 cent per cubic meter for energy may lead to a reduction in pumping hours by farmers who use electricity for irrigation purposes, without significantly affecting the cropping patterns of the region or the output of key cereal crops. The same has been observed by Meenakshi *et al* (2012) in paddy cultivation of dry (*boro*) season in India. We demonstrate the possibility that reforms in subsidy policies to a limited extent may be economically feasible, which have also been recently reported by Springmann and Freund (2022). Our scenario on low-restriction also brings similar levels of water withdrawals by the middle of the century and offers an alternative when pricing policies may be difficult to implement and have higher transaction costs. The reduction caused by this scenario is already sufficient for water conservation, as identified by Baghel *et al* (2018), Bonsch *et al* (2015) and

Hoekstra *et al* (2012), and offers a good alternative when price-related policies cannot be implemented.

Our high price scenario presents a policy alternative to bring about major reductions in agricultural water withdrawals by the middle of century by significantly increasing the cost of water withdrawals. Other global studies have observed that appropriate water policies causing differential water tariffs for consumer groups may bring about the relevant decrease in irrigation water consumption (Qdais and Al Nassay 2001, Gómez-Limón and Riesgo 2004). It has generally been suggested that as prices increase, farmers switch towards more efficient irrigation practices to retain agricultural profits (Berbel *et al* 2019, Oulmane *et al* 2019). This has also been observed in an assessment of groundwater depletion and its impact on agricultural production in Punjab and Haryana in India by Bhattarai *et al* (2021). They report that only when energy prices were increased to substantially high values (by 356%), farmers in approximately half the areas would shift away from paddy crop cultivation, which is similar to a reduction in irrigated croplands (increase in rainfed cropland) in our model. Results from this scenario reflect the fact that high changes in volumetric pricing need to be imposed to induce water saving behaviour among farmers. This is similar to observations made by de Fraiture and Perry (2007). The trade-offs here are an increase in producer profits but at the cost of reduced trade balance. From our results, it can therefore be concluded that twin goals of maintaining existing agricultural production and water conservation can be met with a small increase in energy prices, whereas if the policy goal is to reduce overall water withdrawals, energy prices will need to be increase multifold to cause a change.

Our restriction scenarios offer an alternative policy tool for water governance when pricing policies cannot be implemented. The low-restriction scenario closely aligns with the low-price scenario but with different implications for production, prices and trade, thereby suggesting that it may be possible to implement quotas on water withdrawals with limited impacts on agricultural production, prices and the trade balance. Our findings in this case are in line with the observations of Buchholz *et al* (2016), who found that imposition of water quotas were able to reduce mean number of irrigation applications by farmers, but not water prices. To some extent, this policy is already implemented in some parts of India in the form of restrictions in water supply hours and electricity rationing (Ryan and Sudarshan 2020) and the negative correlation between energy prices and groundwater storage as reported by Bhanja *et al* (2017) also hold true in our case. However, a clear policy strategy that is informed by evidence on future outcomes, including impacts on trade balance is needed, and our paper is a first attempt to shed light onto this knowledge gap.

Due to modelling limitations (elaborated in appendix 1b of SM) both on the supply side and the demand side such as fossil (non-renewable) groundwater and multicropping, our scenarios slightly underestimate water withdrawals in India. While these dynamics cannot be explicitly assessed, we are able to present suggestive evidence on potential implications of tractable policy scenarios for implementation at the national level that traverse the political-economy boundaries of India's policymaking. Our scenario design was motivated to simply assess the trajectories of different policy tools that were designed to arrive at the same goal in the future. The assumptions in our model are driven by existing data and literature, but do not account for other important factors such as governance and implementation challenges. Our modelling framework and scenario design does not allow us to assess other policy alternatives to reduce water and energy subsidy burden—such as prescribing geographies to grow specific crops (Devineni *et al* 2022) or increase in solar energy use to reduce energy subsidy burden (Shah *et al* 2018, Gulati *et al* 2020, Kumar *et al* 2022a, 2022b). Additionally, a simplifying assumption in our analysis is farm-level homogeneity. Therefore, we cannot account for farmer preferences and differences in adjustment behaviour. The aggregate nature of our scenarios does not allow us to shed light on distributional effects on production and consumption decisions that may result from the policies, particularly at the sub-national level. Any implementation of these policies will require a more detailed approach at a spatio-temporal level and requires additional sub-national data and analysis.

5. Conclusions

In this paper, we present potential implications of applying alternative irrigation water policy instruments (quotas vs. pricing) on India's cereal production systems using a global dynamic partial equilibrium model, MAgPIE. Our results identify the benefits and trade-offs of these policy tools on water withdrawal reductions, agricultural production, agricultural prices and profits as well as India's trade patterns for cereal crops. We conclude that it is possible to increase energy prices for agriculture with minimal impacts on agricultural production, prices, and trade of cereal crops, and limit water withdrawals between 16% and 20% by 2050. Similarly, we conclude that significantly reducing human water withdrawals for agriculture can be achieved by increasing energy prices up to four times or by imposing physical restrictions on water withdrawals. Such a substantial price increase, however, has direct implications for prices and producer profits, with the high-restriction scenario eroding profits that can otherwise be gained.

In the absence of state-level information, our simulation results offer a good assessment of potential futures for policy decision making at the national level. Additional analysis needs to be undertaken to evaluate intra-regional implications of the reduction in cultivated areas of cereal crops, production of other important non-cereal crops and impacts of climate change.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.6809773. The model's source code is openly available at https://github.com/magpiemodel/magpie with the specific model version and code used for model runs can be found here (4.5.0) at https://github.com/vartika271987/magpie/tree/waterpaper.

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