LETTER

Sustainable alternative futures for agriculture in India—the energy, emissions, and resource implications

Kaveri Ashok\textsuperscript{1}, Ramya Natarajan\textsuperscript{1,∗}, Poornima Kumar\textsuperscript{1}, Kabir Sharma\textsuperscript{2} and Mihir Mathur\textsuperscript{2}

\textsuperscript{1} Center for Study of Science, Technology and Policy (CSTEP), 10th, No. 18, Mayura Street, Pappanna Layout, Nagashettyhalli R.M.V. 2nd Stage, Bangalore, IN 560094, India
\textsuperscript{2} DESTA Research LLP, ABL Workspaces, G-56, Green Park (Main), New Delhi, Delhi 110016, India

∗ Author to whom any correspondence should be addressed.

E-mail: ramya@cstep.in

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Abstract

India’s falling aquifer levels, erratic monsoons, arable land constraints, stagnating crop yields, growing food demand, and rising greenhouse gas (GHG) emissions necessitate that strategic interventions be planned and implemented to maintain food security in the country. In this paper, we present two novel system dynamics simulation models—termed ‘Sustainable Alternative Futures for India’ (SAFARI) and SAFARI-R (a regionally disaggregated version of SAFARI)—that can be used to develop and analyse specific interventions required at the national and regional levels to sustainably maintain food security. Our simulation results show that increasing micro-irrigation coverage, limiting sugarcane cultivation, and improving water recycling in domestic and industrial sectors can help achieve food production sufficiency within the limitations posed by the availability of natural resources. Alternatively, a behavioural shift towards eating (and cultivating) coarse cereals instead of rice (which is water intensive) is another effective intervention, especially when combined with micro-irrigation or crop yield improvements, and reduced sugarcane cultivation. When compared to a scenario where current practices continue, these alternative pathways to food security can reduce annual water consumption for irrigation by 18%–24%, electricity demand for irrigation by 60%–65%, and the agriculture sector’s total (direct + indirect) GHG emissions by 17%–25%, by 2050. Further, simulations on SAFARI-R indicate that the north, centre, and west zones of the country are considerably pressed for water, while the south and east zones could run out of land. As a way to meet the food demand in these zones in future, the possibility of crop redistribution is explored along with other strategies such as reducing groundwater dependence.

1. Introduction

Balancing a country’s development goals with its climate commitments is a formidable challenge, particularly for developing countries like India. The UN Global Sustainable Development Report \cite{1} states that neither business-as-usual growth nor incremental changes will be enough for achieving a country’s Sustainable Development Goals (SDGs) \cite{2} and fulfilling its Paris Agreement \cite{3} commitments. The report also reviews the trade-offs and co-benefits of achieving the various SDGs, and stresses the importance of studying inter-sectoral dependencies to be able to limit the trade-offs.

One SDG, the achievement of which may have substantial trade-offs, is zero hunger. Health issues like obesity, undernutrition, type II diabetes, and coronary heart disease are attributed to specific dietary patterns. Adopting plant-based diets and avoiding red meat consumption have been shown to reduce these health risks as well as greenhouse gas (GHG) emissions globally \cite{4,5}. However, crop cultivation can also be unsustainable. Excessive dependence on groundwater for irrigation has contributed to its...
depletion in parts of north and east India [6,7]. Fresh-water depletion, in turn, could pose a threat to achieving various SDGs, including zero hunger. Further, crop cultivation also contributes to GHG emissions—methane from flooded rice fields, nitrous oxide from fertiliser use, and energy-emissions from tractors and irrigation pumps [8]. Climate change in turn affects crop yields [9, 10]. Understanding such interlinkages is critical to be able to limit the aforementioned trade-offs and achieve sustained food security in the long-term. Models can aid this process of understanding through scenario analyses and help develop robust strategies.

There are many long-term energy forecasting models with varying purposes, sectoral considerations, and approaches. Some models follow a top-down approach [11, 12] with GDP-driven trajectories, while others adopt a more bottom-up approach [13, 14] and consider development goals too to project future energy demands. However, only a few capture the interlinkages between sectors, and fewer explore non-economic feedback based on water or resources availability [15, 16]. More often, models consider economic feedback based on prices and markets [17]. A recent review [18] of 36 conceptual frameworks linking food security and agriculture concluded that most of them are static analyses with limited representation of non-linearity (feedback loops), and recommended using system dynamics (SD) modelling to effectively capture interdependencies. Applying an SD approach helps identify the unintended consequences of ‘quick fix’ policy solutions to agriculture and natural resource management problems [19], and is useful for longer term modelling.

In this study, we present two novel SD simulation models for India’s agriculture sector with its dynamic interlinkages and physical feedback processes—‘Sustainable Alternative Futures for India’ or the SAFARI model (national scale), and the SAFARI-R model which is regionally disaggregated. The SAFARI model includes various development goals and sectors such as housing, healthcare, education, transport, power, etc., but we focus on food and agriculture in this paper.

India is currently self-sufficient in food grain production but is projected to have shortages in the future as demand increases with population growth [20]. Some of the other oft-stated reasons for this potential shortage are stagnating crop yields, arable land constraints due to urbanisation, poor soil health, erratic monsoons, and groundwater overexploitation [21, 22]. Additionally, the demand for food grains for animal feed has been growing owing to increased demand for animal products. Therefore, our objectives are (a) to estimate India’s food grain demand up to 2050, (b) to explore the policy, technology, and behavioural interventions or strategies required to sustainably meet this demand, and (c) to understand the corresponding implications of these strategies on energy, emissions, land, and water. Through the SAFARI model, we explore scenarios for sustainably achieving and maintaining food security in India up to 2050, to provide insights towards the country’s mid-century long-term strategy [3] development. To test how some of these national-level scenarios would play out in the different regions of India and to develop region-specific scenarios, we built SAFARI-R, using which we have examined cropping pattern shifts and the impact of regional water and land constraints on food security.

2. Methods

2.1. SAFARI model—national

The SAFARI model is essentially a food security ‘goal-seeking’ model, which is constrained by water and land availability. While food security entails many dimensions, our focus is on adequate production of food grains [23] (rice, wheat, coarse cereals, and pulses) to satisfy a set per capita dietary requirement [20, 24, 25]. SAFARI indicates whether food grain production sufficiency is achieved every year, and if not, estimates what the shortage or gap is so that one can then explore strategies to bridge the gap. Figure 1 represents the key variables and architecture of SAFARI’s agriculture module through the use of a causal loop diagram (CLD).

As shown in figure 1, a ‘gap in food grain supply for human consumption’ (after accounting for seed, feed, and wastage) causes ‘area under food grains cultivation’ to expand into available arable land which then results in an increase in ‘food grain production’ and consequently an increase in ‘food grains available for human consumption’ thereby leading to a decrease in the ‘gap in food grain supply for human consumption’. In this manner, the B1 balancing loop is responsible for meeting food grain production sufficiency and is the dominant loop as long as there are no land or water constraints.

When arable land runs out, area under cultivation cannot increase further and therefore a gap in food grain supply builds, thus requiring strategies such as improvements in cropping intensity and yield. Crop yield is a function of fraction of irrigated area under cultivation and the type of irrigation, which changes upon exogenous interventions. Water is modelled as a common stock available for all sectors to draw as per their requirement, subject to water availability (groundwater and surface water) constraints. Agriculture is the largest withdrawer for water; therefore, water constraints have critical implications for food security. The total groundwater and surface water demands for irrigation (from food grains and

3 In the model, intervention strategies are exogenous and user-input-driven.
Figure 1. CLD for the agriculture sector in SAFARI. The ‘+’ and ‘−’ signs represent positive and negative polarities, respectively, between the connected cause-and-effect variables. Exogenous variables are coloured black, endogenous variables are blue (stocks are shown in dark blue), and intervention strategies are in green. The key balancing loops (or negative feedback loops) are indicated by a B# enclosed by a semi-circle arrow. There are no reinforcing loops in this model.
other crops) are calculated in the model endogenously as a function of the average crop water requirement (CWR) per unit area and share of irrigated area, and type of irrigation. When the total water demand (including other sectors\(^4\)) exceeds availability, indicating a water shortage year, the proportionate area is removed from under cultivation (B2a and B2b loops). Therefore, in a water-shortage year, the area increase for bridging the food grain gap (B1 loop) is restricted unless water-saving strategies are implemented.

Overall, these key balancing loops and user-driven interventions dynamically determine system behaviour. While we do report absolute values where possible, the focus has been to identify trends and system behaviour/shape over time in response to various ‘what-ifs’. The strategies reported in this paper are explained in table 1. All input data assumptions are detailed in supplementary table S1.1 (available online at stacks.iop.org/ERL/16/064001/mmedia). For comprehensively modelling the agriculture sector, we have also factored in the area under cultivation for non-food-grain crops (such as sugarcane, oilseeds, fruits, and vegetables).

The area under food grains is modelled as a stock with a bi-flow that either adds or removes area. The change in area under food grains is calculated using the following equation:

\[
\Delta A_f = \begin{cases} 
\text{IF } G_f < 0 \text{ THEN MIN } \left( I_{fw}, \frac{G_f}{Y_f} \right) \text{ ELSE } \left( A_{max} - A_f \right), \frac{G_f}{Y_f} \right) \Delta T 
\end{cases}
\]

where,

- Index \((f)\) represents the four food grains—rice, wheat, coarse cereals, and pulses.
- Index \((w)\) represents causal impact of water shortage.
- \(A\) is the arrayed stock to represent area, in hectares; \(\Delta A_f\) is the change in area under food grain cultivation.
- \(G\) is the variable to represent gap in food grain supply, in tonnes.
- \(Y\) is the variable to represent yield, in tonnes ha\(^{-1}\).
- \(A_{max}\) is the total arable land available for food grain cultivation, in ha.
- \(\Delta T\) is the time step (annual).
- \(I\) represents impact on area, in hectares, which is calculated using the equation:

\[
I_{fw}(T) = \begin{cases} 
\text{IF } (\text{Water demand } (T) - \text{Water supply } (T)) > 0 \text{ THEN } \frac{(\text{water demand } (T) - \text{water supply } (T))}{(\text{CWR})_f} \text{ ELSE } 0 
\end{cases}
\]

where water demand and supply are in cubic metres, and CWR is in cubic metres per hectare.

The energy (electricity, solar, and diesel) required and associated emissions to pump the volume of groundwater required for irrigation are estimated on the basis of the water level depth and average pump power. The number of pumps required is calculated using the following equations:

\[
\text{No. of pumps} = \frac{\text{Ground water demand}}{\text{Average discharge rate} \times \text{Functioning hour per year}}
\]

\[
\text{Average discharge rate (gpm)} = \frac{\text{Pump HP} \times \text{Efficiency} \times 3960}{\text{Dynamic head (ft)}}.
\]

Due to regional variations in variables such as pump capacity (HP) and dynamic head, we assumed a weighted average based on data from the Minor Irrigation Census [26]. Tractors’ fuel energy is also estimated on the basis of the average number of tractors per hectare and mileage.

Fertiliser industry production responds to the demand from the agriculture sector (based on an average annual fertiliser footprint per unit area of cultivation) through the B3 loop.

In addition to food grain requirement per capita, we have also accounted for meat demand per capita (meat being an emissions-intensive sector) and the associated livestock-related water requirement and emissions, as well as food grain requirement for feed. The model is able to capture this competition between food grain availability and feed.

Other non-energy GHG emissions in the model include methane from rice cultivation and direct N\(_2\)O emissions from fertiliser application on managed soils.

Based on recommended per capita nutritional requirements [27] and nutrients present in the food grains of interest [28], we scored the BAU diet and dietary shift scenarios for each nutrient using the formula:

\[
\text{Score}_i = \begin{cases} 
\text{IF } \frac{\text{Supply}_i}{\text{Requirement}_i} \geq 1 \text{ THEN } 10 \text{ ELSE } \left( \frac{\text{Supply}_i}{\text{Requirement}_i} \right) \times 10 
\end{cases}
\]

\(^4\) The SAFARI model has all the energy and water demand sectors—we present only the agriculture-relevant modules in this paper. Water demand for other sectors is detailed in the supplementary material section 2.
Table 1. Descriptions of various what-if scenarios or intervention strategies explored in the SAFARI model in addition to the reference case.

| Scenario                                      | Abbreviation | Description                                                                                                                                                                                                 |
|-----------------------------------------------|--------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Exploitation-as-usual                         | EAU          | In this scenario, water availability is assumed to not be a constraint. Groundwater overexploitation (following current unsustainable cropping practices) is assumed to continue through progressively deeper borewells (depth reaching 100 m by 2050). While this is representative of the current situation in India, it is a hypothetical worst-case scenario because in reality, continued over-extraction of groundwater will lead to disastrous impacts on the environment, which will in turn impact water and food security. |
| Regulated water use                           | RWU          | In this scenario, water use is regulated and only ‘utilisable’ water (1123 BCM) is considered to be the total available water for the country (physical feedback of water constraint). All sectors (agriculture, domestic, and industry) draw water from this pool, and in case of a shortage, the feedback is felt by all of them in proportion to their demand. Thus, agriculture invariably takes the biggest hit when there is water inadequacy. Simulating such a scenario allows us to identify the most effective interventions required to limit water use to within reasonable levels in a climate-constrained world whilst also achieving food security. |
| Micro-irrigation                              | Micro        | Precise irrigation techniques like micro-irrigation help improve crop yields, and also reduce water consumption because of their higher efficiencies. In this scenario, 60% of net irrigated area in 2050 is assumed to be brought under micro-irrigation, which is ~47 Mha. The ultimate micro-irrigation potential for the country has been identified to be around 70 Mha. |
| Regulated sugarcane cultivation              | SC           | Since sugarcane is a water-intensive crop, we explored a scenario where area under sugarcane cultivation is assumed to reduce to 4.5 Mha by 2030 and further to ~4 Mha by 2050 (in EAU and RWU, it would have grown to >10 Mha based on historical trends). |
| Water recycling                               | Reuse        | 50% of all non-potable water for domestic consumption and 70% of industrial water are assumed to be recycled (efficiently withdrawn) by 2050. |
| Moderate effort combination 1                | Mix 1        | This is a combination of moderate-level implementation of the above three scenarios. Micro-irrigation coverage is increased to 15 Mha by 2030 and 34 Mha by 2050 (which is 20% and 40% of irrigated area respectively); 40% of non-potable domestic water and 50% of industrial water are recycled by 2050; and area under sugarcane cultivation reduces to 4.8 Mha by 2050. |
| Dietary shift towards coarse cereals (millets)| Millets      | By 2050, half of water-intensive rice in our diets is replaced by coarse cereals such as millets. The share of coarse cereals in food grain production increases from around 14% (currently) to 33% while rice reduces from 40% (currently) to 20%, by 2050. |
| Limit on domestic meat production             | Meat import  | In this scenario, we explore what happens if the livestock feed requirement does not compete with food grains and instead additional demand is met by imports, thereby easing the pressure on local land and water resources. It is also representative of a scenario where the increase in per capita meat consumption over time is less aggressive. |
| Moderate effort combination 2                | Mix 2        | This is a combination scenario where along with the millets scenario, around 30 Mha is brought under micro-irrigation by 2050 (which will be 35% of irrigated area in 2050), and sugarcane cultivation is limited to 6.8 Mha. |
| Moderate effort combination 3                | Mix 3        | In this combination scenario, millets, SC, and meat import scenarios are assumed to be implemented together along with a yield improvement scenario for coarse cereals where by 2050, 10% of the yield gap (which is the difference between yield and potential yield) is met. |
| Solar pumps                                   | Solar        | 35% of all irrigation pumps are assumed to be solar pumps by 2050 (in RWU, it is 10%). |
where index \((i)\) refers to the nutrient being scored, for instance, protein, fibre, calcium, etc. These scores are shown in supplementary figure S2.1.

Exploring in detail, the impact of climate change on agriculture, is not within the scope of this study. However, based on secondary literature, we have included a few scenarios on how the future food grain gap could be exacerbated by climate change. Using a recent assessment on temperature rise predictions for India \([29]\) and a comprehensive analysis on the impact of temperature rise on crop yields \([10]\), we present three scenarios for climate change along the Representative Concentration Pathways (RCP) RCP8.5, RCP4.5, and RCP2.6 \([30]\).

2.2. SAFARI-R—regional model

In order to examine possible strategies for food security at the regional level, we constructed SAFARI-R. We used hydro-meteorological zoning \([31]\) to determine the resolution for this model. Based on river basins and geography, India is divided into north, west, centre, east, and south zones. The groundwater and surface water availability of each zone was estimated on the basis of average annual precipitation, basin area, and evapotranspiration rates.

The national food grain demand is allocated to each zone based on food grain crop distribution pattern. The same model structure—gap, water, and land loops—was recreated for the five zones by using relevant data sourced from agriculture and water ministry documents (as detailed in supplementary table S1.2). In addition, the water stock for each zone was disaggregated into surface water and groundwater stocks. Figure 2 depicts the SAFARI-R model architecture and table 2 describes the scenarios developed using SAFARI-R.

These scenarios enable the understanding of zonal crop distribution, regional groundwater vulnerability, and arable land constraints and subsequent impacts on food security.

2.3. Data inputs

The modelling horizon for both the national and regional versions of SAFARI is 2050, and the base year is 2011. Initial values for the stocks (i.e. 2011 values) and inputs for other exogenous variables are provided in supplementary tables S1.1 and S1.2. The key data sources are Land Use Statistics, Global Yield Gap Atlas, International Water Management Institute, Central Research Institute for Dryland Agriculture, National Bank for Agriculture and Rural Development, Indian Council for Research on International Economic Relations, Central Water Commission, and FAO \([32–36]\).

2.4. Model validation

Based on recommended validation processes \([37, 38]\) for SD models, we performed some structure and behaviour pattern tests. Results of the behaviour reproduction tests (for 2011–2018, simulated compared with real data) for the national and regional models are in supplementary figures S3.1–S3.13. Additionally, we also ensured dimensional consistency in the model, and performed extreme condition tests (figures S3.14 and S3.15).

3. Results

3.1. Gap in food grain availability

The current total food grain demand for human consumption (after accounting for seed, feed, and wastage) in India is around 240 million tonnes (Mt) and is expected to rise by around 70 Mt by 2050. Owing to stagnating crop yield improvements \([39, 40]\) and growing land and water constraints, meeting this additional demand could be both challenging and energy (and emissions) intensive.

The agriculture sector in India has been responsible for overexploitation of groundwater resources and the resultant falling aquifer levels mainly due to highly subsidised electricity supply \([7, 41]\). An accurate estimate of the remaining groundwater in aquifers is yet to be conclusively established but the average depth of irrigation wells in the country has been increasing consistently \([26]\). We consider this in our exploitation-as-usual (EAU) scenario, as described in table 1, where progressively deeper borewells or other energy-intensive water purification technologies are used to ensure water supply and therefore food security. While such overexploitation is rampant in many parts of the country, some state governments have recently started taking steps towards regulating water use through various policies. Thus, in the rest of the scenarios explored (in table 1), we assume ‘regulated water use’ (RWU) where only utilisable water (1123 billion cubic metres (BCM) per year of renewable groundwater and accessible surface water) is available for use \([42]\). This is a hypothetical ideal scenario, and understandably, moving towards RWU without making arrangements for alternative water procurement strategies will lead to a gap in food grain supply (figure 3(a)) caused by a feedback from water constraint. Here, we have examined some interventions that could help bridge the gap in food grain supply in RWU by 2050.

Considering that micro-irrigation increases crop yields and reduces water consumption \([43]\), it seems to be a powerful intervention that reduces the food grain supply gap by half by 2050. Water-related interventions in non-food-grain sectors, e.g. reducing area under sugarcane cultivation or domestic and industrial water recycling, reduce the gap by around 30% by 2050. A combination of aggressive micro-irrigation coverage and regulated sugarcane cultivation (Micro + SC) can completely bridge the food grain gap up to 2050. Many less aggressive or
moderate combinations of these individual interventions can bridge the gap by 2050; we present a few examples here (as listed in table 1). If our current diets continue, Mix 1 which is a combination of moderate micro-irrigation coverage, reduced sugarcane cultivation, and water recycling, can completely bridge the gap in food grain supply by 2050. In the Mix 1 scenario, B2a is the dominant loop between 2030 and 2037 (where the gap increases due to water shortage), and beyond 2037 B1 becomes the dominant loop to eventually bridge the gap.

The total groundwater demand for rice, wheat, coarse cereals, and pulses in 2019 was 250, 108, 35, and 6 BCM, respectively, and the corresponding surface water demand was 140, 60, 20, and 4 BCM, respectively. Rice cultivation is the major factor responsible for groundwater exploitation and has one of the lowest economic and physical water productivities [44]. Therefore, we have considered a dietary-shift-led crop diversification scenario where by 2050, half of rice in our diets is replaced with coarse cereals such as millets and maize (figure 3(b)).

Figure 2. Schematic diagram and zonal CLD for SAFARI-R. The zonal sub-models are driven by the food grain demand for each zone, which is based on zonal allocation of the national demand (exogenously) taking into account cropping patterns. Each sub-model then tries to meet the annual demand to limit food shortage. Total food grain gap from SAFARI-R model reported is the sum of the individual zonal dynamic gaps.
Table 2. Descriptions of various what-if scenarios explored in the SAFARI-R model based on two kinds of diets—a business-as-usual diet and a dietary shift towards coarse cereals.

| Diet type                                      | Scenario                                      | Abbreviation | Description                                                                 |
|-----------------------------------------------|-----------------------------------------------|--------------|-----------------------------------------------------------------------------|
| Business-as-usual diet where rice and wheat   | Reference                                     | BAU diet_Ref. | This is a reference case scenario where cereal production continues to be distributed among the five zones as per current patterns. |
| dominate cereal consumption as per current    | Cereal crop redistribution                     | BAU diet_Redist. | In this scenario, we explore the impact of shifting water-intensive rice cultivation away from water scarce regions such as the north, centre and west zones to the south and east zones. By 2050, rice production from the north, centre and west zones reduces to 7.5% of total rice produced in the country (they currently produce 32% of the total). We also reduce wheat contribution from these regions to 70% (from 80% today). |
| trends                                         | Groundwater management                         | BAU diet_GW  | Considering the annual replenishable groundwater resources and withdrawal for irrigation, groundwater dependency of irrigation is assumed to linearly reduce from 72% to 45% in the north; 56% to 45% in the south; 75% to 50% in the centre and west; and 70% to 50% in the east, by 2050. |
| Land use management                            | BAU diet_Land                                 |              | The south, east, and west zones have a lower cropping intensity than the national average, and are poised to have arable land constraints in the future. In this scenario, we assume that cropping intensity in the south and west zones will increase to 150% and 138% respectively (from 124%), and in the east zone will increase to 165% (from 140%) by 2050. This would increase the national average cropping intensity from 143% to 156% by 2050. |
| Dietary shift towards coarse cereals such as  | Cereal crop redistribution                     | Millets      | In this scenario, coarse cereals are assumed to be equally distributed across the five zones by 2050, and the share of wheat in the north, centre, and west zones is further reduced to 60%. |
| millets, away from rice                        | Groundwater management                         | Millets      | This scenario assumes reduction in groundwater dependency of north, centre and west zones to 45% by 2050. |
|                                               | Land use management                            | Millets      | In this scenario, cropping intensity in the south and west zones is increased to 150%, and that of the east zone to 165%. In addition, a slight improvement in the average yield of coarse cereals is assumed (bridging 5% of the potential yield gap by 2050). |

In addition to reducing the gap by around 30%, this strategy has co-benefits as well: first, millets are more climate resilient than rice varieties and can better tolerate diverse abiotic stresses [45]; second, methane and N₂O emissions from rice cultivation—contributing around 20% of the agriculture sector GHG emissions in India [46]—can be reduced, and third, millets have a lower glycaemic index and are a healthier alternative to rice [47] (in terms of providing riboflavin, calcium, and fibre) as shown in supplementary figure S2.1. The trade-off, however, is that coarse cereals typically have a lower yield compared to rice and therefore require more land to attain the same production. This is why the millets scenario does not entirely bridge the gap and in fact increases it slightly in the beginning—while water shortage is no longer a problem, land is. This drawback can be addressed by increasing the area under micro-irrigation because it leads to improved yields [43], as explored in the Mix 2 scenario, or by pushing for higher yielding varieties of coarse cereals as considered in Mix 3. Limiting domestic meat production scenario is another effective ‘add-on’ as it eases the food-vs-feed competition. This is particularly the case for the dietary shift to millets scenario because coarse cereals form the largest share of feed among other food grains [48]. The inverted U shape seen in all the dietary shift scenarios indicates a change in loop dominance from B2a/b to B1 around 2034–37. A combination of the millets scenario with reduced sugarcane cultivation and water recycling in other sectors (Millets + SC + Reuse) can keep the gap
lesser than or equal to zero throughout the modelling horizon.

3.2. Implications of the zero-gap scenarios
Of the interventions presented, there are six scenarios in which the food grain gap is completely bridged by 2050—EAU, Mix 1, Mix 2, Mix 3, Micro + SC, and Millets + SC + Reuse. In addition to achieving food security, the modelled interventions have implications on energy/electricity demand, GHG emissions, and arable land and freshwater resources. Table 3 shows these implications for 2050 as a representative year.

In EAU, the total electricity demand for irrigation increases to more than twice as high as those for the other scenarios because of the progressively deeper borewells. Considering that state governments across India spend around INR 90,000 crore per year on electricity subsidies to farmers (at around INR...
Table 3. Implications of the zero-gap scenarios in 2050 as a representative year. Electricity demand for irrigation, non-energy agriculture GHG emissions, total agriculture sector GHG emissions, net land cultivated, and irrigation water demand.

| Intervention scenario | Electricity (TWh) | Non-energy GHG (MtCO$_2$e$^a$) | Total GHG (MtCO$_2$e$^b$) | Land demand (Mha) | Water demand (BCM) |
|-----------------------|-------------------|-------------------------------|--------------------------|-------------------|-------------------|
| EAU                   | 424               | 556                           | 915                      | 175               | 1170              |
| Mix 1                 | 161               | 535                           | 759                      | 172               | 966               |
| Mix 2                 | 151               | 508                           | 730                      | 177               | 900               |
| Mix 3                 | 150               | 510                           | 689                      | 169               | 904               |
| Micro + SC            | 150               | 521                           | 737                      | 169               | 892               |
| Millets + SC + Reuse  | 156               | 518                           | 747                      | 181               | 939               |

$^a$ Includes enteric fermentation methane emissions in livestock, methane from rice cultivation, and direct N$_2$O emissions from fertiliser application in soil.

$^b$ Includes non-energy GHG emissions in addition to emissions from producing electricity for irrigation, combustion emissions from diesel use in pumps and tractors, and emissions from fertiliser production.

4.5 kWh$^{-1}$), we estimated that shifting to any of the other scenarios (from EAU) could save the government at least INR 22 lakh crores by 2050 (cumulatively, in today’s value)$^5$.

The difference in electricity demand in 2050 between Mix 1 (BAU diet) and Mix 2 or Mix 3 (coarse cereals diets) is around 6%–7%, while that between Mix 2 and Mix 3 is less than 1%. However, when we examine the non-energy agriculture GHG emissions, the differences between Mix 1, Mix 2, and Mix 3 become more pronounced. This is because Mix 2 and Mix 3 have lower rice methane emissions (due to the shift towards coarse cereals), and Mix 3 has lower domestic livestock emissions owing to meat imports. The cumulative reduction (2020–2050) in agriculture sector non-energy GHG emissions by switching from EAU to Mix 1, Mix 2, Mix 3, Micro + SC, and Millets + SC + Reuse scenarios is 404, 867, 1116, 606, and 553 Mt CO$_2$e, respectively.

When energy-related emissions are also considered, shifting from EAU to the other scenarios could lead to a 17%–25% reduction in annual emissions by 2050, with Mix 3 resulting in the most savings (of 226 Mt CO$_2$e). Switching on the solar pump scenario can further bring down annual emissions by almost 30–35 Mt. The cumulative reduction (2020–2050) in total agriculture sector GHG emissions by switching from EAU to Mix 1, Mix 2, Mix 3, Micro + SC, and Millets + SC + Reuse scenarios is 3.23, 3.84, 4.16, 3.6, and 3.23 billion tonnes (Gt) CO$_2$e, respectively.

Switching from EAU to the other scenarios reduces the emissions intensity of food grain cultivation as shown in figure 4. The maximum reductions are for rice and wheat (over 30%), followed by coarse cereals in the Mix 3 and Millets + SC + Reuse scenarios. Overall, the emissions intensity of food grain production decreases by 14% while switching to Millets + SC + Reuse, 16% for Mix 3, 20% for Mix 2, and over 20% for Micro + SC and Mix 1.

3.3. Impact of climate change

Due to the negative impact of temperature rise on crop yields, by 2050, there could be an additional gap in food grain supply of around 30 Mt in RCP8.5, 16 Mt in RCP4.5, and 1.6 Mt in RCP2.6 according to our analysis (annual numbers in supplementary figure S2.8). This is based on the direct negative impacts of climate change on yield, and does not include the impact of changes in rainfall or atmospheric CO$_2$. As the yields drop, more land needs to be cultivated to meet the demand, and the observed gap in food grain supply is due to arable land constraints. Increasing the cropping intensity would bring down the gap. In reality, climate change would also impact water availability which would also pose constraints on crop cultivation. However, due to lack of appropriate data on current and future (up to 2050) groundwater availability in India, we chose to examine only the direct impact of climate change on yield. Further, our RWU and related scenarios already look at a water-constrained future and therefore the strategies proposed would be relevant for climate-change-imposed water constraints as well.

3.4. Regional context—results from SAFARI-R

All the scenarios presented so far are important from a national-level strategy planning point of view, especially towards India’s LTS formulation. In SAFARI-R, we customised the SAFARI model for the five hydro-meteorological zones within India to explore regional strategies like shifting water-intensive crops away from water scarce areas, etc as described in table 2.

Figure 5 shows the total food grain gap (added up from the different zones) under the scenarios described. In the regulated water use (RWU) scenario, which is our hypothetical case scenario where...
Figure 4. Emissions intensity of food grain production. The total GHG emissions (from energy for irrigating food grains, production and application of fertilisers for food grain cultivation, and rice methane) to produce one tonne of rice, wheat, coarse cereals, and pulses under our zero-gap scenarios in 2050 are shown in this graph.

4. Discussion

In this study, as described earlier, principles of systems thinking were adopted to generate scenarios which tend to be 'shape' scenarios rather than 'range' scenarios (which economic models typically forecast [49]). For instance, the food grain supply is driven by demand and constrained through feedback from water and land availability, leading to unique shape scenarios as shown in figures 3 and 5. It is evident from these figures that the food grain shortage follows a similar trend and shape in both the national and regional models. The regional model estimates an 11% higher gap than the national model in 2050 (∼11 Mt) in the RWU scenario without additional interventions. This difference is due to the fact that the regional model has separate stocks of groundwater and surface water for each zone; thus, the groundwater issues of the NCW zones further amplify the gap.

While the water constraint imposed in the RWU scenario could in fact become a reality (due to climate change [50] or a volumetric pricing system for water [51]), we have primarily used it as a hypothetical scenario to explore demand-management strategies. In a simulation environment, it helps explore the question how do we maintain food security in a future water-constrained world? We have shown that increasing micro-irrigation coverage, reducing sugarcane
Figure 5. Projected gap in food grain availability from SAFARI-R in various scenarios. The results are aggregated for the national level from the regional version of the model, SAFARI-R. Crop redistribution, reducing groundwater dependence, and increasing cropping intensity are the strategies analysed for the two diet types—BAU and millets as described in table 2.

cultivation, recycling of water in other sectors, reducing groundwater dependence and shifting to surface water use, dietary shifts away from rice, increasing cropping intensity, and yield improvements are all effective strategies to varying degrees. SAFARI-R demonstrates the zone-wise importance of each intervention strategy. For example, yield improvements through micro-irrigation, or increased cropping intensity are more important for the south and east zones since they could run out of arable land. Water-based interventions such as reducing rice or sugarcane cultivation and reducing groundwater dependence are more crucial for the NCW zones. Crop redistribution strategies where water-intensive crops are shifted away from water-scarce regions do have some positive impact but most often also end up shifting the water problems to the new region. So to be effective in the long-term, crop redistribution must be combined with other strategies such as reduced groundwater dependence and improved yields (through micro-irrigation or new varieties).

There are of course some limitations and caveats worth noting about our modelling study. First, adopting micro-irrigation could lead to farmers cultivating more water-intensive crops or expanding their irrigated area thereby negating the water-saving potential of micro-irrigation. We have not accounted for such a rebound effect of efficiency improvement in our study. Second, we have not explicitly modelled costs of production or profits, and instead looked at the system from a more biophysical angle. Considering that the agriculture sector in India is heavily regulated and driven by policy rather than markets, and the fact that costs will also be affected by the biophysical constraints, we believe that the trends observed in our model will continue to hold true. In our zero-gap scenarios, the electricity subsidy savings (of around INR 55 000–100 000 crores per year) can be diverted towards improving farmer incomes, however, further detailed analysis on farmer welfare is an important area for future research. Third, a dietary shift towards coarse cereals (and away from water-intensive crops like rice) is a personal choice and could be difficult to implement, however, the benefits seem to far outweigh the trade-offs. In addition to nutritional health benefits, shifting away from rice cultivation could potentially avoid the air-pollution-inducing menace of stubble burning in North India every winter, thereby resulting in indirect health benefits. Moreover, the otherwise hard-to-abate rice methane emissions will also be avoided. There is already a policy push for growing and eating more millets, and with the right behavioural nudges, this scenario could be realised. Fourth, we analysed the impact of climate change on food grain production as separate scenarios for RCP2.6, 4.5, and 8.5, instead of adding on to our what-if strategies. This is because each of our strategies could put us on
a different temperature rise trajectory which might skew the results if combined. Finally, while we have tried our best to ensure that the scenarios presented here are reasonable, this is predominantly a what-if analysis so we have not examined in detail the feasibility of farm-level implementation or under specific situations.

5. Conclusion
SAFARI is a novel SD simulation model developed to be a decision-support tool that can be used to generate hundreds of user-driven scenarios, specifically towards formulating India’s LTS. The SAFARI model can also be customised for other countries or regions—we replicated the structure for five regions within India (north, west, centre, south, and east) based on river basins and geography, to create the SAFARI-R model, also presented in this paper.

India’s total food grain demand is expected to reach around 310 Mt in 2050. Using the two models, we have selected and discussed some alternative pathways to sustainably meet this demand (food security) in India. The most effective strategies to achieve food security within the limitations posed by natural resources availability include:

(a) Increasing precise irrigation (such as micro-irrigation) coverage to 34–50 Mha, and limiting sugarcane cultivation to 4–5 Mha by 2050.

(b) A dietary shift where half of the rice that we consume (and cultivate) today is replaced by coarse cereals by 2050, combined with a yield improvement strategy such as micro-irrigation or development of high yielding varieties of coarse cereals (where the average yield of coarse cereals increases from around 1.25 t ha\(^{-1}\) today to 1.8–2 t ha\(^{-1}\) in 2050).

(c) Reducing ground water dependence across regions to 45%–50% by 2050 (compared to ~70% today) and shifting rice cultivation away from the NCW regions to the south and east.

These alternative pathways have lower water, land, energy, and emissions footprints when compared to the unsustainable EAU scenario.

While we have presented our scenarios and analyses from SAFARI and SAFARI-R, the ultimate intended utility of these models lies in users being able to develop their own scenarios based on their unique priorities. The user interface of the SAFARI model has been designed and will be published online for easy access.

Data availability statement
The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iD
Poornima Kumar @ https://orcid.org/0000-0002-5851-1319

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