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Quantifying crop yield gaps across the IGP from new perspectives – production, farmer profit and sustainability of water use.

FINAL REPORT - ACIAR project WAC/2018/169

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Ethics

The activities reported herein have been conducted in accordance with CSIRO Social Science Human Research Ethics approval 011/17.

Contents

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Executive summary

In this report we have used a combination of regional records, on-farm trials, on-station experiments and cropping systems modelling to examine the variation in 3 key types of crop yield gaps for major cereal crops (rice, wheat, maize) across the Indo-Gangetic Plain (IGP). Those are the *Physiological Yield Gap* (the difference in yields between what farmers currently produce and what is physiologically possible at that location), the *Economic Yield Gap* (the difference between yields that farmers currently achieve and the yields which result in maximum farmer profit at that location), and the *Water-sustainable Yield Gap* (a measure of the water-resource sustainability of current crop production at that site). We have conducted new modelling using the APSIM cropping systems model, employing data and previous model setups from the Sustainable and Resilient Farming Systems Intensification in the Eastern Gangetic Plains project ('SRFSI') (ACIAR CSE-2011-077), as well as additional CIMMYT work in the mid- and Western Gangetic Plains sites .

The key findings of this research are:

Physiological Yield Gaps

- Farmers in the far Western Gangetic Plains (WGP, for example, Haryana) operate closer to the physiological potential yield for major crops, whereas farmers of the Eastern Gangetic Plains (EGP) and much of the mid-IGP (MGP), have greater physiological yield gaps and greater potential to increase their current crop yields.
- The average physiological yield gap in the MGP sites (Varanasi, Nepalganj, Sunsari, Patna) is around 30% of potential yield for rice, and similar for wheat. For the EGP sites (Coochbehar, Dinajpur, Malda, Rajshahi), the figure is around 20% for rice, 25% for wheat, and 20% for maize. By contrast, in the far WGP (Karnal in our analysis) the yield gap for rice is around 2-3%, and 8% for wheat.
- On average, the implementation of *conservation agriculture* (CA) practices reduces physiological yield gaps by around 5% (in comparison with *conventional tillage* (CT)) for crops across the IGP.

Economic Yield Gaps

- We found that to maximise their economic returns under existing cost-price structures IGP farmers should be aiming for within 1000 kg ha^{-1} of potential crop yields to provide optimal economic outcomes and lessen the risks of aiming for maximum potential yield.
- Conservation agricultural practices improved gross margins by 20-30% over conventional tillage across the lesser developed parts of the IGP (MGP and ESP) with smaller gains in the far WGP.
- Implementing CA practices, together with economically optimising fertiliser N and irrigation inputs, is recommended for less developed sites thought the Mid- and Eastern Gangetic plains, and our analysis indicated this could lead to gross margin gains of 29-59% over current farmer practice.
- Electricity subsidies have a significant effect on farmer profitability in the far WGP, but the effect of these subsidies decreases with less rice in the system, due to decreased GW pumping. For example, when substituting maize for rice to achieve sustainability.

- The price that farmers receive for their grain is the most influential aspect in determining their profit. Cost of irrigation came next, with cost of nitrogen fertiliser the least influential of the factors we considered.

Water-sustainable Yield Gaps

- Cropping districts in the far WGP (our example: Karnal, Haryana) currently overexploit GW resources and are farming unsustainably with their current cropping practices. This is evident from the groundwater extraction data we have assembled, and from the dynamics of groundwater depth (see Appendix 3, summarised in Figure ES1 below). This is also supported by many reports from the literature.

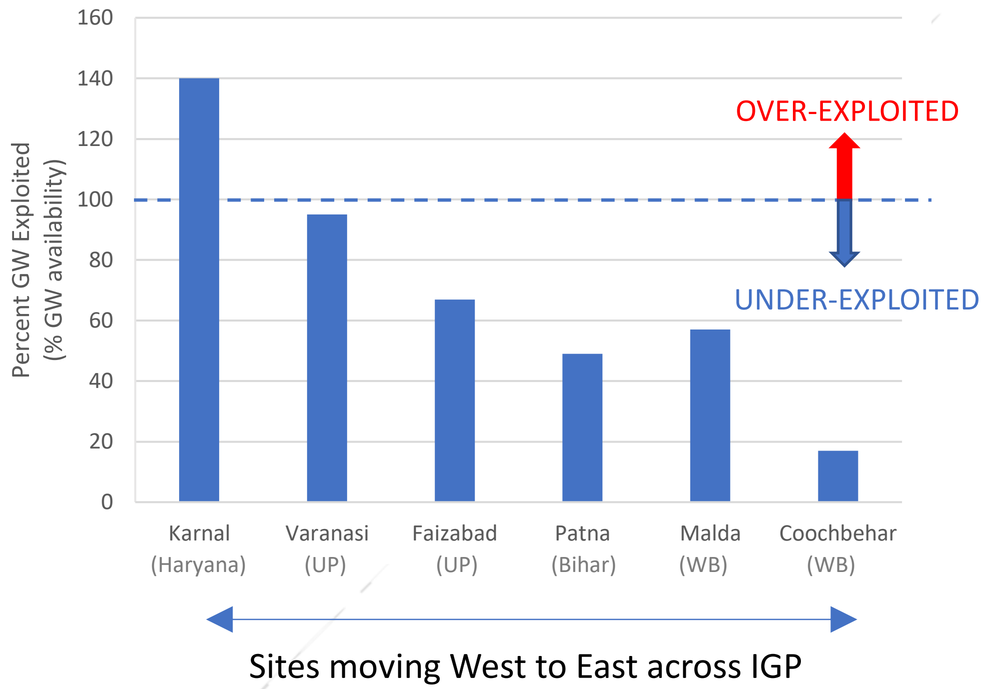

Figure ES1. Variation in ground water (GW) resource exploitation percentage, moving from West to East across the IGP. Data collated from the Indian Central Ground Water Board (see Appendix 1). Percentage GW exploitation = (current net GW draft / net GW availability) * 100

- This trend is also evident from our analysis using an independent measure of cropping system water-sustainability for the IGP (cumulative Rain – APSIM-simulated cumulative ET curves, over multiple years in sequence). When these curves trend in a positive direction for a cropping system, it is considered 'water-sustainable'. When they trend in a negative direction, it predicts that a cropping system will ultimately over-exploit local water resources (see Figure ES2). Figure ES2 illustrates the water-resource impact of a range of different cropping systems at each site (different coloured curves. These include rice-wheat, rice-maize, rice-rice, with and without CA). The measured groundwater trends which we collated (Figure ES1) correlate strongly with our APSIM simulations on water-sustainability (Figure ES2), giving some confidence in our methodology and results., but also suggesting that.
- We examined cropping system adaptation options for over exploited cropping systems in the WGP. Rice irrigation is primarily responsible for over-exploitation of groundwater resources in the region.

Our analyses for Karnal (Haryana) indicate that modifying the current rice-wheat system to (40% rice:60% maize in kharif) followed by 100% wheat in Rabi is both sustainable and profitable for the region. India needs that missing 60% rice to be grown somewhere, however.

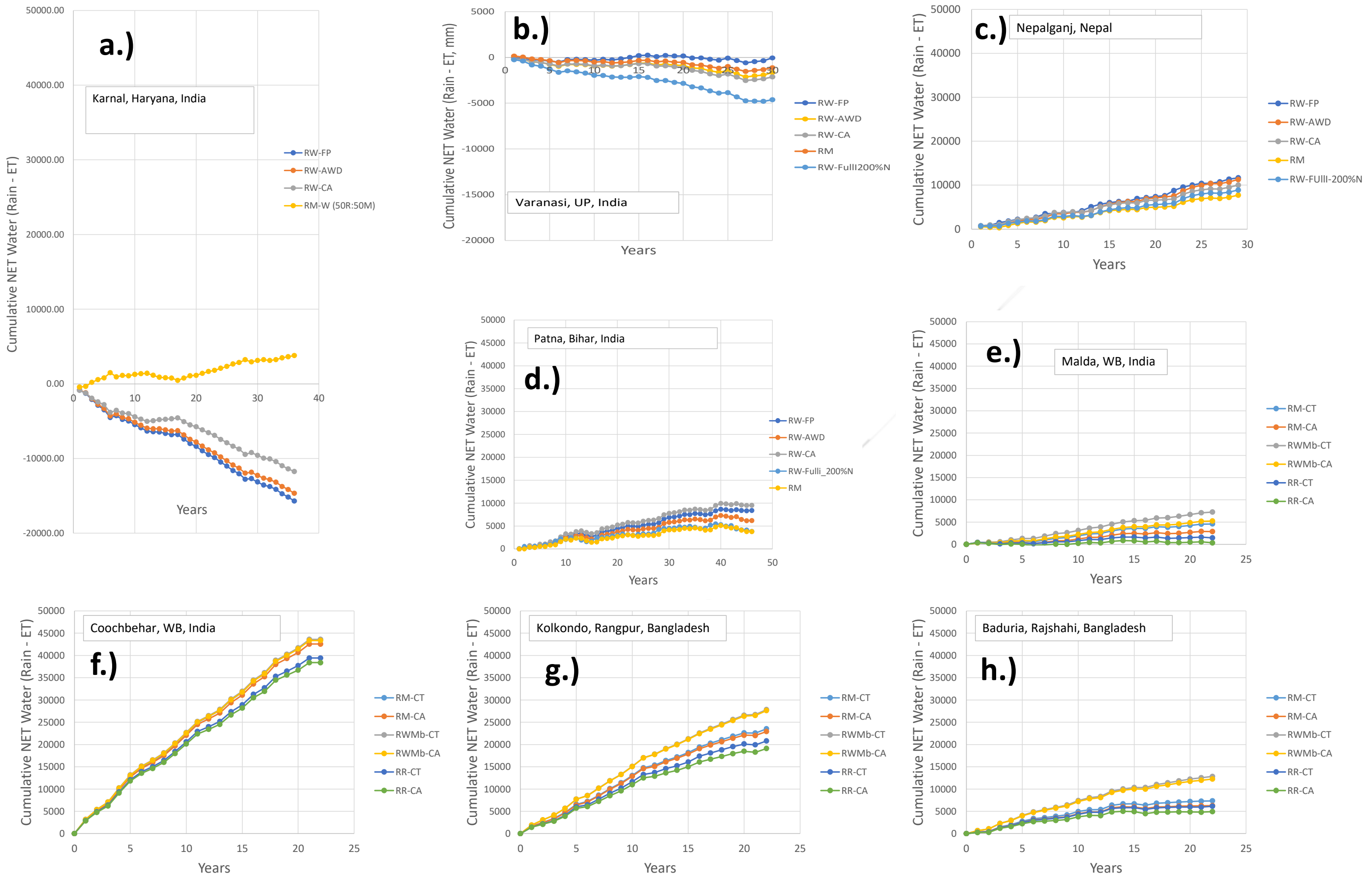

Figure ES2: Summary of *water sustainability* of key farming practices across the IGP sites chosen for this research analysis, simulated using APSIM. Y-Axis is cumulative Net Water (rainfall – ET), plotted against Time (years) on the X-Axis. Sites depicted are (a) Karnal, Haryana, India; (b) Varanasi, UP, India; (c) Nepalganj, Nepal; (d) Patna, Bihar, India; (e) Malda, WB, India; (f) Coochbehar, WB, India; (g) Kolkondo, Rangpur, Bangladesh; and ((h) Baduria, Rajshahi, Bangladesh.

- Our analysis also suggests that many of the EGP sites examined are significantly underexploited from the perspective of water-resources. It is impossible to make a blanket statement that the EGP is 'underexploited', however our analysis indicates that some sites are highly underexploited (for example Coochbehar and Rangpur, Figure ES2 *f* and *g*), whereas some are marginal (for example Malda, Figure ES2 *e*).
- Most EGP sites are well-positioned to increase total rice production, although not just in the Kharif season. We conducted APSIM simulation of irrigated rice-rice (kharif-Rabi) systems across all EGP sites, and found that the system was water-sustainable everywhere, although some sites were standouts for water availability (Coochbehar, Rangpur. Figure ES2). This suggests the possibility of

shifting key rice production eastwards into the EGP in future, to relieve the pressure of rice production on overexploited water resources in the WGP.

- It also calls into question the current focus on 'crop diversification' in the EGP, and raises the question as to whether the EGP is not better suited to 'rice intensification' to carry a larger load of India's rice production – with more crop diversification (less water-intensive non-rice cropping) to be encouraged in the currently over-exploited WGP?
- Conservation Agriculture (CA) practices have a minimal effect on the water-sustainability story, due to minimal differences in ET between CA and conventional tillage (CT) practices.

Overall Recommendations:

- The planning and commissioning of a comprehensive study of the IGP, focussed on evaluating scenarios for strategically balancing future crop production with available water resources across, regions, focussing on balancing the whole IGP water-food nexus/system. Such a study would need to integrate knowledge from hydrologists, agronomists, economists, spatial and GIS specialists, climate change experts, and people with insights into local and national political constraints and issues, and would aim to produce a strategic blueprint to guide regional water-resource development and agricultural production aspirations across the whole IGP. This would require a spatially integrated assessment of various future cropping system and water-resource options, instead of a point-based analysis such as this SRA presented. This could be achieved by linking cropping systems modelling with GIS layers, remote sensing, and regional water-resource modelling.
- Further study into policies and strategies to encourage farmers to bridge economic yield gaps, and also the cost-benefits of governmental levers to bring economically viable crop yields closer to physiological ones.

1 Introduction

1.1 Background

Feeding the world's growing population into the future will demand greater productivity from existing agricultural land (Alexandratos and Bruinsma, 2012). Quantifying food production capacity from current farmland in a consistent and transparent manner is vital for policy makers, researchers, and farmers (Van Ittersum et al., 2013). The traditional concept of a crop yield gap (the difference between what farmers are currently achieving and what is physiologically possible at that location; Becker et al., 2003, Angulo et al., 2012, Grassini et al., 2015a, 2015b) is considered to be useful in national food security planning and determining what food increases are possible with improved practices, varieties or technologies. The scientific literature is actually dominated by research into this physiological yield gap, however in reality the concept may be of limited practical value. We propose there are other lesser-known or lesser-considered 'yield gap' definitions which may be more useful to farmers, extension efforts, and policy-makers than the physiological yield gap. This particularly applies to the IGP where socio-economic constraints often limit options and over-exploitation of regional water resources has caused problems in the recent past (for example, the Indian Punjab has been heralded for its technical achievements in past decades but increasingly criticized for leveraging its success on the environment (Jalota et al., 2007).) These other yield gap definitions include what we will call (i) the economic yield gap (difference between farmers current yields and the yields which would generate the maximum farmer profit) and (ii) the sustainable-water yield gap (defined by the maximum regional crop yield possible, while keeping irrigation water extractions (surface and ground-water) sustainable).

These three crop yield gaps (physiological, economic, and sustainable-water) may all correspond to different crop yield levels, and those differences may vary between geographical location, soil environment, and socio-economic setting (Fig. 1). Detailed understanding of these different crop yield gaps (and how they vary across the IGP) is currently non-existent but highly desirable. For example, policy makers need to know not just what is physiologically possible in terms of crop production, but more importantly what is economically and environmentally sustainable. Governments have some control over economic and environmental factors - for example, subsidies or tax structures could be established to encourage farmers to produce at levels above their current economic optimum to achieve national food-security goals, or to produce at lower levels to meet sustainability goals (Figure 1). Ultimately, however, governments cannot implement wise policies without first understanding the goal-posts – and this cannot be achieved without the backing of robust science.

Precise spatially-explicit knowledge about these different yield gaps is essential to guide sustainable intensification of agriculture. A systems approach is also desirable, as modifications made to management of one crop in a rotation (for example, rice or wheat) will likely have direct consequences on the performance of other crops (Ahmad et al. 2014; Balwinder-Singh et al., 2015a; 2015b; 2016). An understanding of potential yield and yield gaps enables us to define opportunities for more detailed studies to identify underpinning causes and the evaluation of new technologies or a changing climate. Bridging, or decreasing, existing crop yield gaps to any of these proposed levels may require utilisation of additional fresh water (ground or surface) resources and applied fertilisers, as part of a 'package' which also includes enhanced varieties and agronomic practices.

Identification of biophysical drivers behind yield gaps can be complex and expensive using experimental techniques alone, as many factors may be involved (fertilizer and irrigation strategies, pest control, genotype, environment and cultural practices, across broad geographical areas), hence cropping system models like APSIM (Holzworth et al., 2014; Gaydon et al., 2017) are ideal tools for this work. However, to prepare a model for this type of investigation (calibrate and validate) information is required on climate, soils, farmer management practices, as well as historical yield records and/or experiment data.

There is a large amount of knowledge in the published literature about crop yield gaps and methodologies, however this is not evenly distributed over the earth and there are numerous developing countries where little data exists, even regarding physiological yield gaps (see Global Yield Gap Atlas http://www.yieldgap.org/). In a thorough examination of the literature undertaken as part of preparing this SRA proposal, we could find no research from any country which explicitly details how bridging crop yield gaps impinges on regional fresh-water resources (both ground and surface). For example, to bring a region's crop production up to maximal yield, how much extra water resources are required? How would this hypothetical extraction impact the sustainability of the resource in that country? The scale of this question is broad, affecting farmers, regional water resource managers, and food security policymakers across the developing world.

We consider this SRA to be a demonstration or 'proof of concept'. In this project we will begin the process of determining these different crop yield gaps across the IGP, and understanding how they are influenced by geography, resource dynamics (climate and water), economic settings, and future climate outlooks. We will employ a combination of cropping systems modelling, economic analysis, farmer engagement, and data-sourcing. We will maintain a primary focus on the EGP as per SDIP aims, but to provide perspective and comparison will include the whole IGP (minus Pakistan – see later note) in our analyses. Our proposed methodology will centre around 8-10 sentinel sites chosen across the IGP region, at which detailed analysis will be undertaken.

We suspect that, if judged to be successful and useful, the methodologies and protocols developed during this 12 month project can potentially facilitate a much broader analysis of the whole region in a subsequent project, bringing in the latest GIS, satellite and remote-sensing technologies, together with the latest economic and climate forecasts, to provide robust insights for regional policy-makers and other stakeholders.

1.2 Relevance for ACIAR and past work

The understanding of yield gaps and available fresh-water resource interactions aligns closely with all ACIAR partner country priorities in food security. Government policy-makers in all countries are likely to be concerned with knowledge about (i) maximum crops yields possible (with no nutrient or water constraints), (ii) crop yields which maximise farmer profits (as a function of various cost/price factors which government may or may not have some degree of control over (for example, fuel subsidies, electricity costs etc)), and (iii) realistic maximum yields farmers should aim for without over exploiting regional water resources. If maximising food production is a primary focus of the government, then there may be interest in the degree to which they might need to subsidise farmers to produce at levels above their economic maximum yield. Similarly, if the maximum sustainable-water grain yields are at a level below the farmer economic optimum yield, then government policy-makers may need information to help them consider options to either (i) provide disincentives for farmers to aim for higher yields, or (ii) subsidise farmers to limit their production and agronomic inputs. If current farmer yields are below all these defined levels (physiological, economic optimum, or sustainable-water optimum) then government policy makers can use this information to evaluate options to encourage farmers to produce more.

ACIAR has undertaken little targeted 'yield gaps' work, per se, however many projects have generated vital data which can be used for APSIM-based research in this area (including ACCA (LWR-2008-019), SAARC-Australia Project (LWR/2010/033), SRFSI (CSE-2011-077), LWR/2009/046, LWR/2010/081), and also on regional water resources (LWR/2003/026, LWR/2001/001, LWR/2001/014). Also the CSIRO-SDIP-Indus project (lead by Dr Mobin Ahmad) has gained significant insights into bio-physical drivers for yield gaps in the Pakistani Punjab rice-wheat system, and has published two papers in Field Crops Research looking into physiological yield gaps in that region, their causes and agronomic interventions needed to economically bridge them (or to minimise Economic Yield Gaps) (Khaliq et al., 2019; Gaydon et al., 2021).

1.3 Conservation agriculture – how does this impact the story?

1.3.1 Principles and importance

Conservation agriculture is a cropping systems philosophy that encapsulated three principles: (1) reduced soil disturbance, (2) residue retention on the soil surface and (3) crop rotations (Hobbs et al., 2008, FAO 2002, 2011).

Cheesman et al (2017) found that implementation of conservation agriculture principles did not result in closing of physiological yield gaps in maize systems of Zimbabwe, although others state that CA is the cornerstone of bridging 'management yield gaps' (Jat et al., 2011), and that CA can lead to optimizing crop yields, largely through helping to address nutrient rundown. CA in South Asia is reported to improve the economics of cropping, particularly through reduction in tillage and labour (Islam et al., 2020; Gathala et al., 2020; Laing et al., 2019), however other research claims that the economic benefits are by no means clear-cut everywhere and that CA can increase or decrease farm profits, depending on the context (Pannell et al., 2014). Aspects which make CA less economically attractive include the opportunity cost of crop residues for feed rather than mulch, the short-term reduction in yields under zero tillage plus mulching (Largely driven by N immobilisation), combined with short planning horizons and/or high discount rates of farmers, farmer aversion to uncertainty, and constraints on the availability of land, labour and capital at key times of year. It has also been suggested that in some cases partial adoption (ie a subset of CA components) can sometimes be superior to full adoption (Chaki et al., 2021a, 2021b; Pannell et al., 2014).

Given this reported heterogeneity in outcomes for CA in smallholder cropping systems, we have sought to examine the effects of Conventional Practices (CT) versus CA in our modelling study into the different types of yield gaps, hopefully helping to answer the questions:

- Does CA help bridge physiological yield gaps at our SRFSI sites?
- Does CA increase Economically optimum yields?
- Does CA contribute to the Water Sustainability of cropping systems in the EGP region? – particularly from the perspective of GW resources.

1.4 Our definitions of "Yield Gaps"

There is a large amount of knowledge in the published literature about crop yield gaps and methodologies, however this is not evenly distributed over the earth and there are numerous developing countries where little data exists (see Global Yield Gap Atlas http://www.yieldgap.org/). These countries include Pakistan, Nepal, Sri Lanka, Thailand, Cambodia, Laos, Vietnam, and Malaysia. Also, prior to our work on this project, we could find no research from any country which explicitly details how bridging crop yield gaps impinges on regional fresh water resources (both ground and surface). For example, to bring a region's crop production up to maximal yield, how much extra water resources are required? How would this hypothetical extraction impact the sustainability of the resource in that country? The scale of this question is broad, affecting farmers, regional water resource managers, and food security policy-makers across the developing world.

The yield gap definitions which we focus on in this report include what we will call (i) the *physiological yield gap*; (ii) the *economic yield gap* (difference between farmers current yields and the yields which would generate the maximum farmer profit) and (iii) the *sustainable-water yield gap* (defined by the maximum regional crop production possible, while keeping irrigation water extractions (surface and ground-water) sustainable).

1.4.1 Physiological Yield Gap

Quantifying food production capacity from current farmland in a consistent and transparent manner is vital for policy makers, researchers, and farmers (Van Ittersum et al., 2013). The differences between potential yield levels (limited only by soils and climate) and actual farmers' yields define crop 'physiological yield gaps' (Becker et al., 2003, Angulo et al., 2012, Grassini et al., 2015a, 2015b). Precise spatially-explicit knowledge about these yield gaps is essential to guide sustainable intensification of agriculture. A systems approach is also desirable, as modifications made to management of one crop in a rotation (for example, rice or wheat) will likely have direct consequences on the performance of other crops (Ahmad et al. 2014; Balwinder-Singh et al., 2015a; 2015b; 2016). Several 'yield gaps' can be defined (Van Ittersum et al., 2013), including the absolute physiological yield gap (maximum yield) and the economic yield gap (that which maximises farmer profit). An understanding of potential yield and yield gaps enables us to define opportunities for more detailed studies to identify underpinning causes and the evaluation of new technologies or a changing climate. Identification of biophysical drivers behind yield gaps can be complex and expensive using experimental techniques alone, as many factors may be involved (fertilizer and irrigation strategies, pest control, genotype, environment and cultural practices), hence cropping system models like APSIM are ideal tools for this work. However, to prepare a model for this type of investigation (calibrate and validate) information is required on climate, soils, farmer management practices, as well as historical yield records and/or experiment data.

1.4.2 Economic Yield Gap

There are valid reasons why farmers don't seek to grow the maximum physiological yield possible. This is illustrated in APSIM simulations for Dinajpur (Figure 3) which shows that maximum physiological yields are regularly higher than those which maximise farmer profit, or gross margin (GM). This is easily explained by referring to the most fundamental law in Economics – the law of diminishing returns. In this case, as N fertiliser inputs are increased from low levels, there are corresponding increases in crop yields and GM. At some point however the increasing cost of more N becomes less than the income from gain in crop yield, and the GM or profit begins to fall. This defines the point of maximum profit. However, our analysis has so far found that for all sites, current farmer yields are considerably below this 'economic maximum. We are currently analysing (for all sites) how +/- 10% and 20% subsides/taxes on each of electricity, fuel, and fertiliser N cost affect the location of this optimum point, and hence the farmers' economic yield gap. We are also conducting analyses on the impact of grain price variation. The results of these analyses will be detailed in the final report.

1.4.3 Water Sustainable Yield Gap

Water-sustainable yield gaps were conceptualised on the same framework as economic yield gaps above, however here the focus was not on maximising farmer profit, but on maximum sustainable exploitation of the groundwater resource (Figure 3)

In practice, though, these *sustainable-water* yield levels are more difficult to define than both *physiological* and *economic* yield gaps because other ways exist to reduce groundwater extraction than just by limiting the number of irrigations or limiting yield. For example, if a particular region was overexploiting its GW resources, then either yields could be limited (as per Figure 3), or else yields maintained but overall cropping area limited. Also, data on actual groundwater exploitation status and cropping area under different cropping rotations was not available at all our sentinel sites.

We calculated Net Cumulative Water (Rainfall - ET) on a daily basis for each site and for each cropping system we analysed as a measure of whether the relevant cropping systems lost more or less water than incoming rainfall. This provided our measure of the 'water sustainability' of each cropping system under consideration.

2 Methodology

The research strategy was at its core a desk-top modelling analysis, informed by substantial targeted on-ground data-sourcing. Data was obtained through engagement with farmers, local scientists/economists, meteorological organisations. Where possible, we used existing data and model setups. The project focussed activities on the primary food crops of the IGP region (rice and wheat, but also maize were applicable and data was available), and sought to gain a broad insight into the relevant crop yield gaps (and their variability) across the IGP. The regional focus will be achieved though the philosophy of representative sentinel sites, at which detailed analyses will be undertaken.

Long-term APSIM scenario simulations will be analysed to reveal the relevant crop yield gaps, and the findings detailed in a final report and journal paper. The analyses contained therein will seek to look for commonalities and contrasts across the IGP and assign relevant drivers to differences. Outstanding knowledge gaps will also be identified and documented.

The effect of CASI technologies and changing economic drivers (cost of fertiliser Nitrogen, cost of irrigation, and price of grains) was also examined via system sensitivity analyses and detailed in section 3 below.

The analysis strategy took the same form at each site, however details and outcomes obviously varied. The economic analyses were relatively simplistic for the purposes of this 1-year SRA and did not require significant involvement of a specialist economist or GIS/remote-sensing specialist, however more detailed economic, climate and geographical analyses are envisioned for a follow-on project – suggested in section 5.2 *Recommendations*.

2.1 APSIM approaches

2.1.1 Selection of sentinel sites

An initial planning meeting was held between CSIRO and CIMMYT (Don Gaydon and Balwinder Singh) in New Delhi (7-8 February 2019), followed shortly after by a stakeholder (Research, Government, NGO) meeting in Kathmandu (coinciding with ACIAR-SDIP Foresight4Food meeting, 9-13 Feb 2019). At the initial meeting, sentinel sites (section 2.5) were selected aiming to adequately represent the diversity of cropping management and environments across the IGP, but also to capitalise on previous research investments - in other words, sites with abundant and accessible data and, where possible, previous successful modelling efforts. These sites included SRAFI sites in the Eastern Gangetic Plain (EGP) and well-researched CIMMYT sites in the Western IGP. Stakeholder views on these selected sites, and on the proposed scope of the research were obtained during the Kathmandu meeting.

2.1.2 Collection of site data

For each of the sentinel sites, the following data was collected and used in APSIM model setup:

- Climate (historical)
- Soils (see Appendix 1)
- Local farmer management details and decision-making logic (see Appendix 2)
- Socio-economic data (gross-margin elements – see Appendix 2)

- Regional historical crop yield records and/or experimental data. This was SRFSI data in the EGP sites.
- Groundwater extraction data for irrigation and any hydrological estimates on degree of groundwater resource over- or under-exploitation. These were obtained largely from the Central Groundwater Board in India (See Appendix 3). No similar data was found from Bangladesh or Nepal.

2.1.3 Parameterise, calibrate and validate APSIM at each sentinel site

All measured and collected data was input into the model, estimates were made for unknown or uncertain parameters, and the model was run for the periods covered by experimental datasets. Comparisons were then made between observed data versus APSIM simulated outputs, and uncertain input parameters were then iteratively modified as required (within reasonable range) until acceptable model performance was achieved (the standard approach for calibrating and validating a cropping system model; Gaydon et al., 2017). Robust statistics were derived to validate model parameterisation and calibration veracity and confirm when model is ready for subsequent scenario simulations and yield gap analyses.

2.1.4 Conduct scenario analyses (using APSIM) to define yield gaps

The APSIM model was then run to simulate grain production (and risk) over the historical climatic record, for a range of scenarios:-

- current farmer practice
- potential grain yield - with no limitations of soil nutrients and water, and only climatic limitations (to define physiological yield gap)
- maximum economic grain yield - consisting of current famer practice with incrementally increased inputs of water and fertiliser, until farmer gross margins are maximised (to define economic yield gap)
- maximum sustainable-water grain yield – limit the available farmer irrigation water according to the identified sustainable water extraction levels (yields) for the district (to define sustainable-water yield gap).

Analysis was then conducted to reveal how yield gaps (physiological, economic, and sustainable-water) varied over the IGP. We then also conducted sensitivity analyses to understand how these yield gaps are influenced by the prevailing cost-price structures. Specifically, in different parts of the IGP, how is the economic yield gap effected by these 3 key elements: (i) N fertiliser costs; (ii) irrigation cost; (iii) grain prices?

2.2 Physiological Yield Gaps

In this study we have examined three yield values for major crops across our IGP sites in investigating Physiological Yield Gaps:

- *District farmer yields* (where available) represent the country or region's records on average yields that farmers are achieving. These will spread across different soil types, crop rotations, and farmer resourcing and skill levels.
- *Simulated farmer yields*. These are APSIM-simulated crop yields, for both CT and CA management practices, derived using the APSIM model – calibrated and validated using the 3 years SRFSI on-farm trial data (Gaydon et al., 2020). For this analysis, these yields were simulated over a longer period

using extended climate files from each location (varied between 25-35 years). For the SRFSI sites, *SRFSI* recommended management was used in the APSIM model. For non-SRFSI sites in the Western IGP, typical farmer management practices were used.

- *Simulated potential yields*. These are APSIM-simulated crop yields for primary local varieties of the major cereal crops, derived as per the Simulated farmer yields however without any limitation on water and nutrients available to the crop. By definition these are related to soil and climate constraints only but vary year to year with different season type. For that reason, the potential yields were similarly simulated over a 25-35-year period and presented as average values with associated error bars (representing the variability in potential yields over the simulated period)

2.3 Economic Yield Gaps

Amongst the biggest factors causing crop yield gaps globally is fertiliser N (Khaliq et al., 2019). For each sentinel site and each relevant cropping pattern examined (for example, rice-wheat rotation) we conducted a range of long-term scenarios, incrementally increasing fertiliser nitrogen inputs to the system. The APSIM model also responded to increased crop growth by applying increased amounts of irrigation water. For each of the scenarios, we calculated long-term gross margins associated with increased N fertiliser, specifically looking for the point at which gross margins (farmer profit) is maximised. This will generally be different from the point at which grain yield is maximised (Figures 1 and 2)

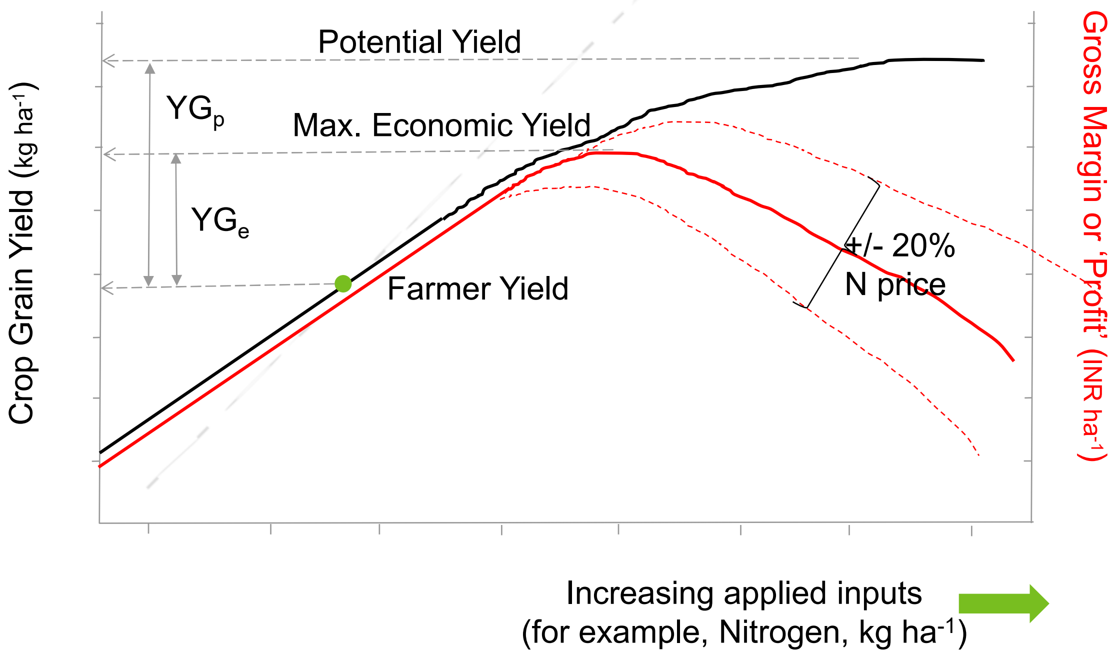

Figure 1. Illustration of how maximum physiological yield differs from maximum economic yield, as inputs to the system are increased.

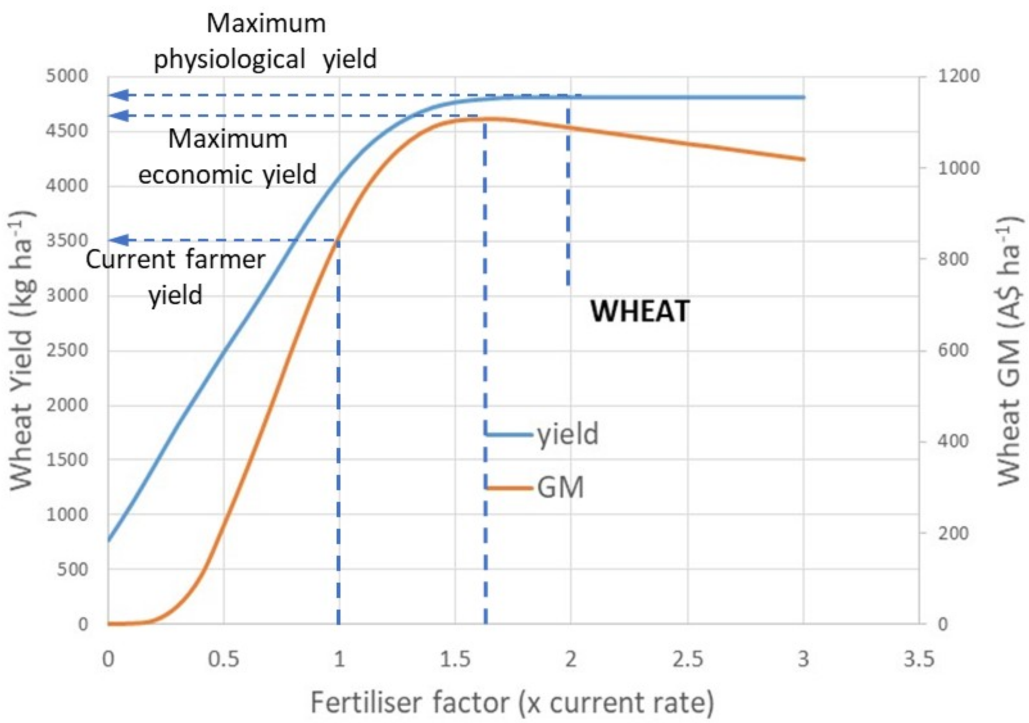

Figure 2. APSIM simulation showing the relationship between wheat production and gross margin (GM) for wheat in Dinajpur, presented as a function of applied N fertiliser. Real data shown from this analysis.

2.4 Water-Sustainable Yield Gaps

Water-sustainable yield gaps were conceptualised on the same framework as economic yield gaps above, however here the focus was not on maximising farmer profit, but on maximum sustainable exploitation of the groundwater resource (Figure 3)

In practice, though, these *sustainable-water* yield levels are more difficult to define than both *physiological* and *economic* yield gaps because other ways exist to reduce groundwater extraction than just by limiting the number of irrigations or limiting yield. For example, if a particular region was overexploiting its GW resources, then either yields could be limited (as per Figure 3), or else yields maintained but overall cropping area limited. Also, data on actual groundwater exploitation status and cropping area under different cropping rotations was not available at all our sentinel sites.

We therefore calculated Net Cumulative Water (Rainfall - ET) on a daily basis for each site and for each cropping system we analysed as a measure of whether the relevant cropping systems lost more or less water than incoming rainfall. This provided our measure of the 'water sustainability' of each cropping system under consideration. ET was defined as crop transpiration (Ep) + soil or pond evaporation (Es). We considered a range of cropping systems at each site, including rice-wheat (R-W), rice-maize (R-M) and rice-rice (R-R), as well as certain other adaptation options for overexploited sites (provided in more detail below in section 3. Although the water-availability at a particular site is more hydrologically complex, this was the only option open to us within the bounds of a 1-year desktop modelling analysis. In any case, this is generally considered to be an acceptable measure of assessing the sustainability of a cropping system, an integrates issues around ground and surface water flowing into and out of a region (Humphreys et al., 2010; Balwinder-Singh et al., 2015a, 2015b) (Figure 4)

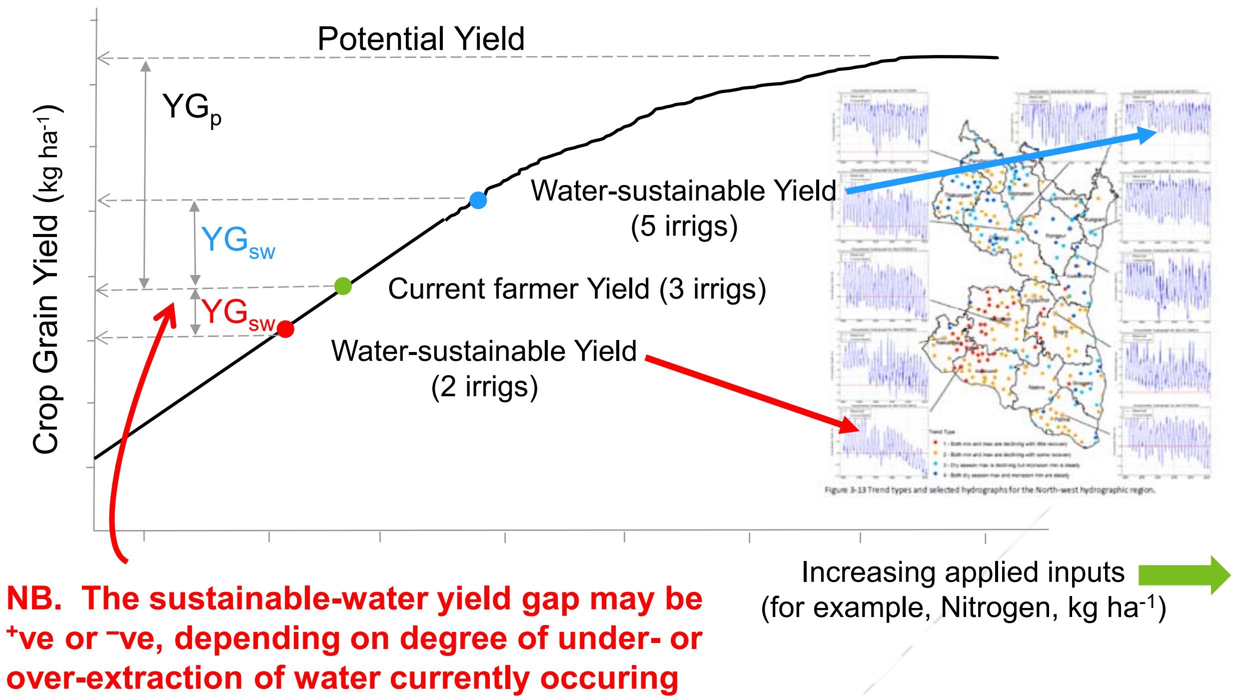

Figure 3. Conceptualisation of the water-sustainable yield gap

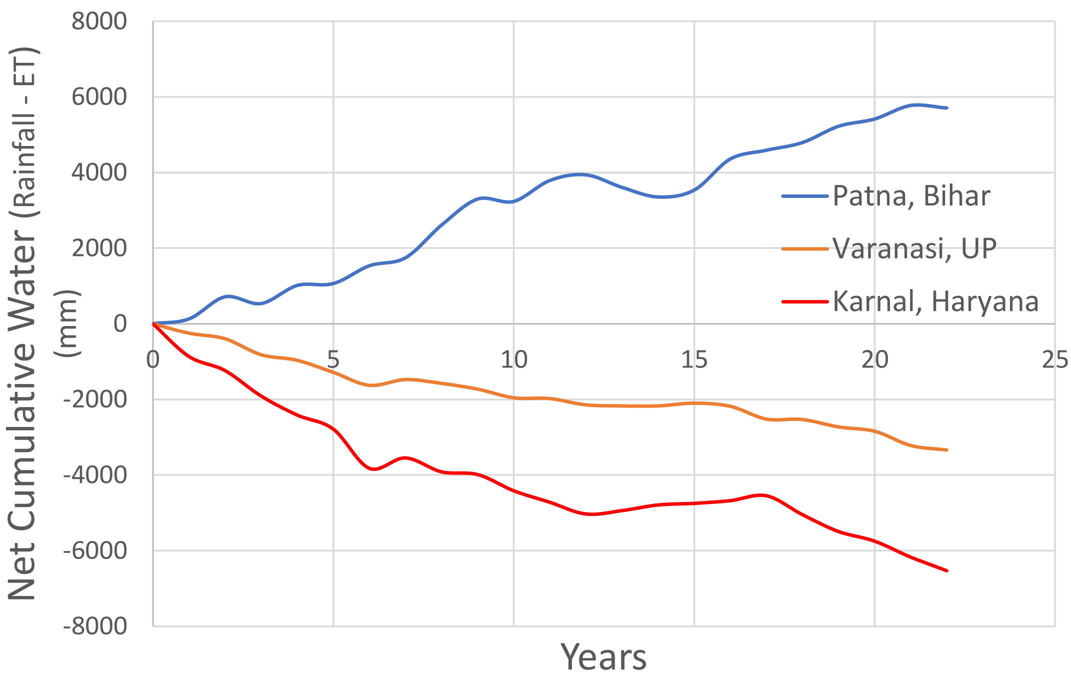

Figure 4. The concept of 'Net Cumulative Water' calculated daily as rainfall minus ET, shown here for *high-input* rice-wheat cropping systems in Patna, Varanasi and Karnal (1983-2018). Such calculations indicate that both Varansi and Karnal are losing more water in losses than is entering system via rainfall, indicating unsustainability. For Patna, the rainfall exceeds water losses, thereby indicating sustainability. Data shown was generated from this research (see section 3.3). (Note, lower-input farmer practice at Varanasi is less intensive and seems sustainable (see section 3.3.3).

2.5 Sites of Analysis

Figure 5 illustrates the sentinel sites chosen for these analyses. These sites were selected aiming to adequately represent the diversity of cropping management and environments across the IGP, but also to capitalise on previous research investments - in other words, sites with abundant and accessible data and, where possible, previous successful modelling efforts. These sites included SRFSI sites in the Eastern Gangetic Plain (EGP) and well-researched CIMMYT sites in the Western IGP.

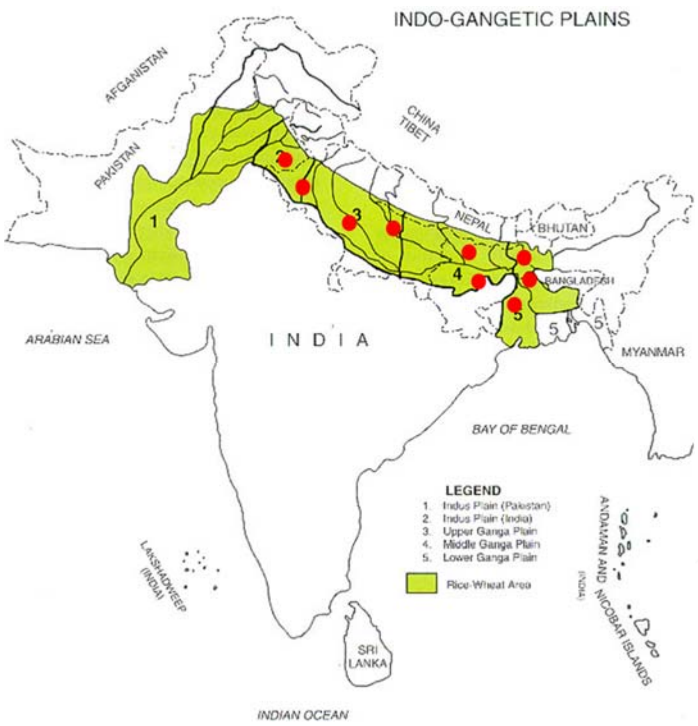

Figure 5. Sites chosen as sentinel sites for this analysis cover a broad transect of the IGP, including data-rich sites from the SRFSI project and also CIMMYT project sites in the MGP and WGP.

- **Karnal, Haryana, India** (latitude 29° 42′ 57″ N, longitude 76° 58′ 18″ W)
- **Varanasi, Uttar Pradesh (UP), India** (latitude 27° 16′ 20″ N, longitude 83° 0′ 9″ W)
- **Nepalganj, Western Terrai, Nepal** (latitude 28° 3′ 16″ N, longitude 81° 37′ 16″ W)
- **Tarahara, Sunsari, Eastern Terrai, Nepal** (latitude 26° 42′ 16″ N, longitude 87° 15′ 22″ W) (SRFSI)
- **Patna, Bihar, India** (latitude 25° 35′ 35″ N, longitude 85° 5′ 3″ W)
- **Malda, West Bengal (WB), India** (latitude 24° 57′ 55″ N, longitude 88° 8′ 21″ W) (SRFSI)
- **Coochbehar, West Bengal (WB), India** (latitude 26° 24′ 15″ N, longitude 89° 23′ 23″ W) (SRFSI)
- **Dinajpur, Bangladesh** (latitude 25° 44′ 42″ N, longitude 88° 40′ 25″ W) (SRFSI – Apurbo Chaki, PhD site, BMWRI)
- **Baduria, Rajshahi, Bangladesh** (latitude 24° 20′ 29″ N, longitude 88° 43′ 3″ W) (SRFSI)

3 Results

3.1 Physiological Yield Gaps

3.1.1 Summary of Potential Yield Gap across the IGP

We have compared APSIM-simulated farmer yields with physiological potential crop yields, also simulated using APSIM (over multi-decadal time periods, using available long-term climatic data). Also, where the data was available, we compared with SRFSI farmer yields from the project field trial sites. In summary, the far West of the IGP (represented in this analysis by Karnal, Haryana, but also largely representative of Punjab) has finely tuned cropping systems where farmer yields are approaching potential yield. Sites examined in the mid-IGP (Varanasi, UP and the two Nepali sites (Nepalganj and Sunsari)) exhibited the significantly greater physiological crop yield gaps, whereas sites in the EGP were mixed – some with larger, some with lesser yield gaps. There was no distinct pattern in crop yield gaps moving from West to East, apart from the substantially lower yield gaps in the far West (Figure 6, Table 1)

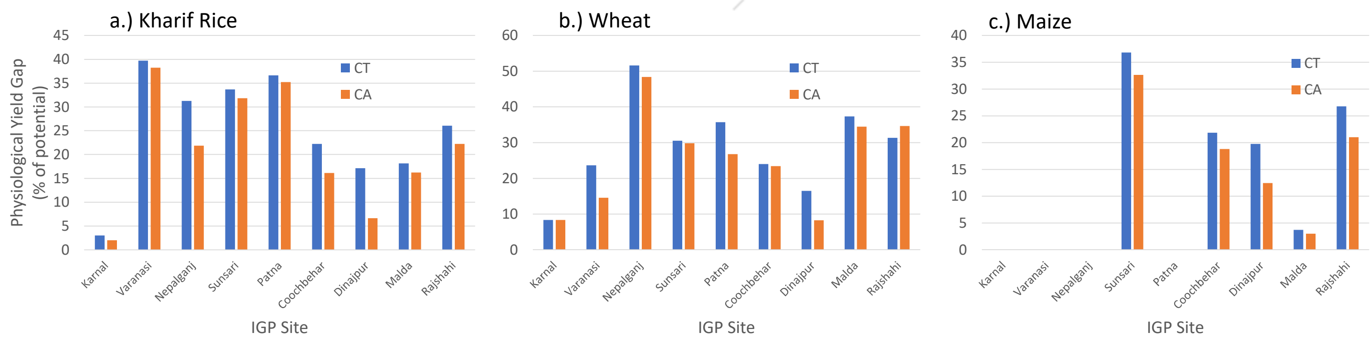

Figure 6. Physiological crop yield gaps (expressed as a percentage of potential yield) for the IGP sites examined in this analysis and the major cereal grains a.) Kharif Rice, b.) Wheat, and c.) Maize. The impact of tillage practices is indicated by the blue (CT) and orange (CA) bars. All figures are simulated using APSIM.

Table 1. Potential yields of the key cereal crops across the IGP sites, together with the percentage crop yield gaps in CT and CA systems.

Site	Kharif Rice		Wheat		Maize	
	Potential Yield (kg ha^{-1})	Yield Gap (CT/CA) (%)	Potential Yield (kg ha^{-1})	Yield Gap (CT/CA) (%)	Potential Yield (kg ha^{-1})	Yield Gap (CT/CA) (%)

Karnal	6400	3/2	6000	8/8	No data	No data
Varanasi	6800	40/38	5500	24/15	No data	No data
Nepalganj	6400	31/22	6200	52/48	No data	No data
Sunsari	7077	34/32	3996	31/30	13096	37/33
Patna	7100	37/35	5600	36/27	No data	No data
Coochbehar	6890	22/16	6964	24/23	11459	22/19
Dinajpur	5613	17/7	4964	16/8	9981	20/12
Malda	6371	18/16	6078	37/34	8165	4/3
Rajshahi	6050	26/22	6180	31/35	8113	27/21

Specific details on individual sites are provided in the following sections.

3.1.2 Karnal, Haryana, India

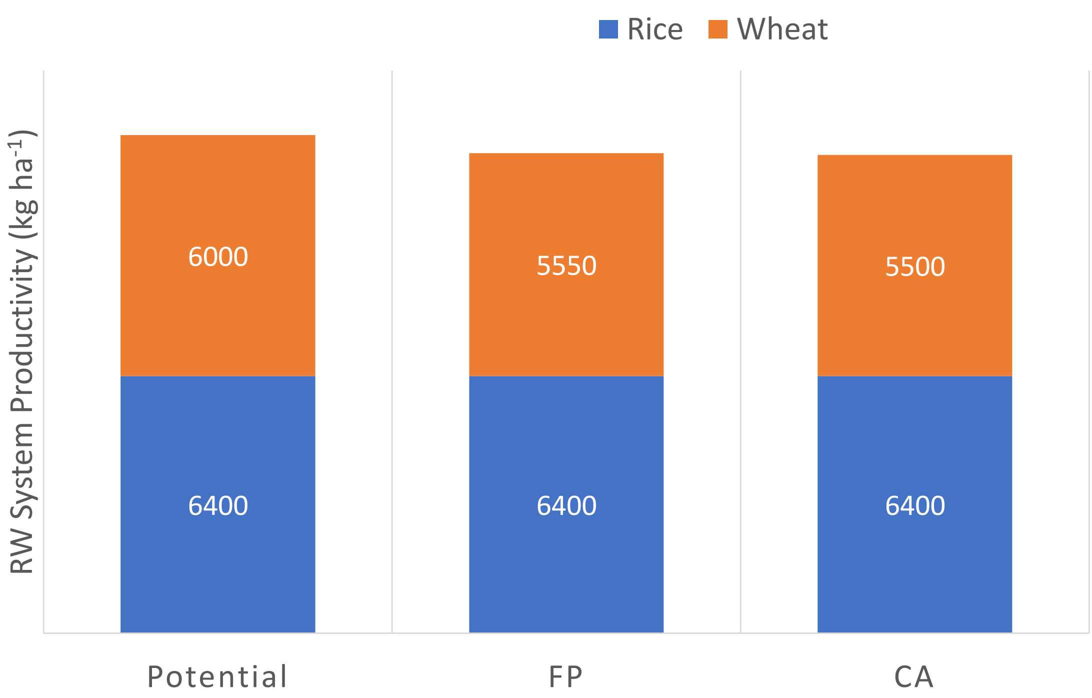

Figure 7. APSIM-simulated productivity of the rice-wheat system in **Karnal, Haryana, India** (1984-2018), showing (from left to right) (i) potential production; (ii) typical farmer practice; (iii) farmer practice following CA principles

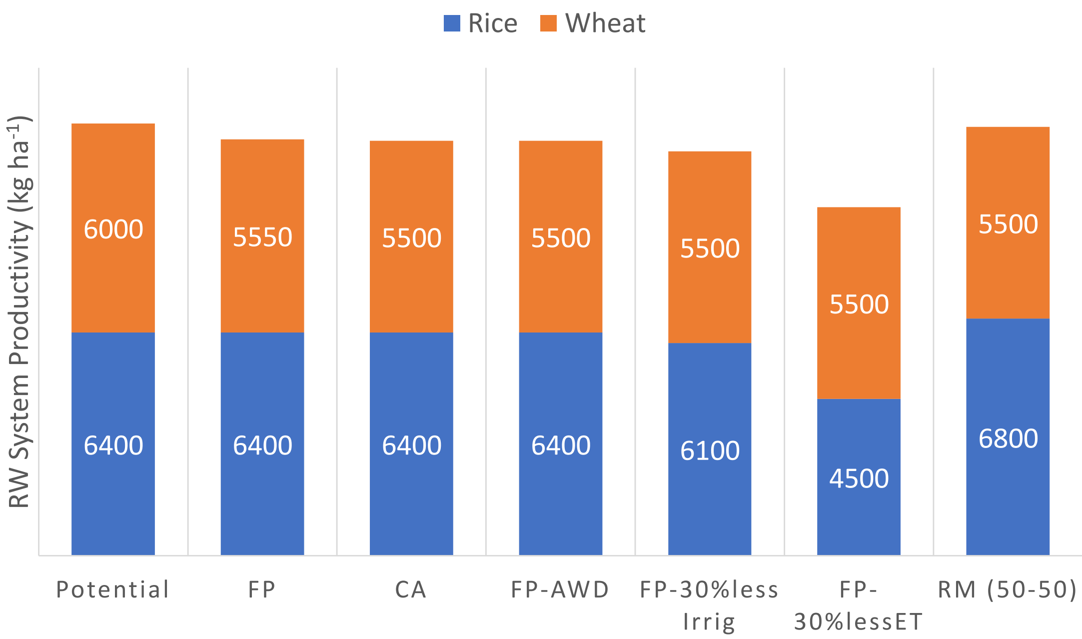

Figure 8. APSIM-simulated productivity of the rice-wheat system in **Karnal, Haryana, India** (1984-2018), showing (in addition to those treatments above in figure 7, from left to right) (i) farmer practice + AWD; (ii) farmer practice with 30% reduction in irrigation for rice; (iii) farmer production with 30% reduction in ET for rice; and (iv) a 50-50 rice-maize mix in the kharif, following farmer practice, with 100% wheat in Rabi. These additional treatments are particularly relevant in consideration of 'water-sustainability' (Section 3.3)

3.1.3 Varanasi, UP, India

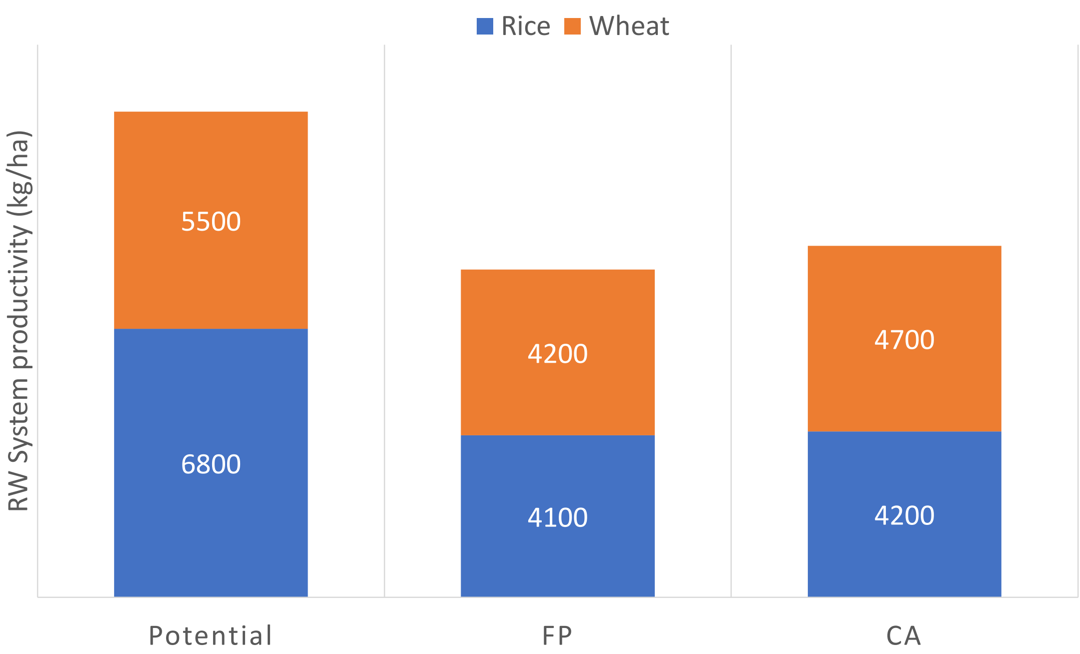

Figure 9. APSIM-simulated productivity of the rice-wheat system in **Varanasi, UP, India** (1987-2017), showing (from left to right) (i) potential production; (ii) typical farmer practice; (iii) farmer practice following CA principles

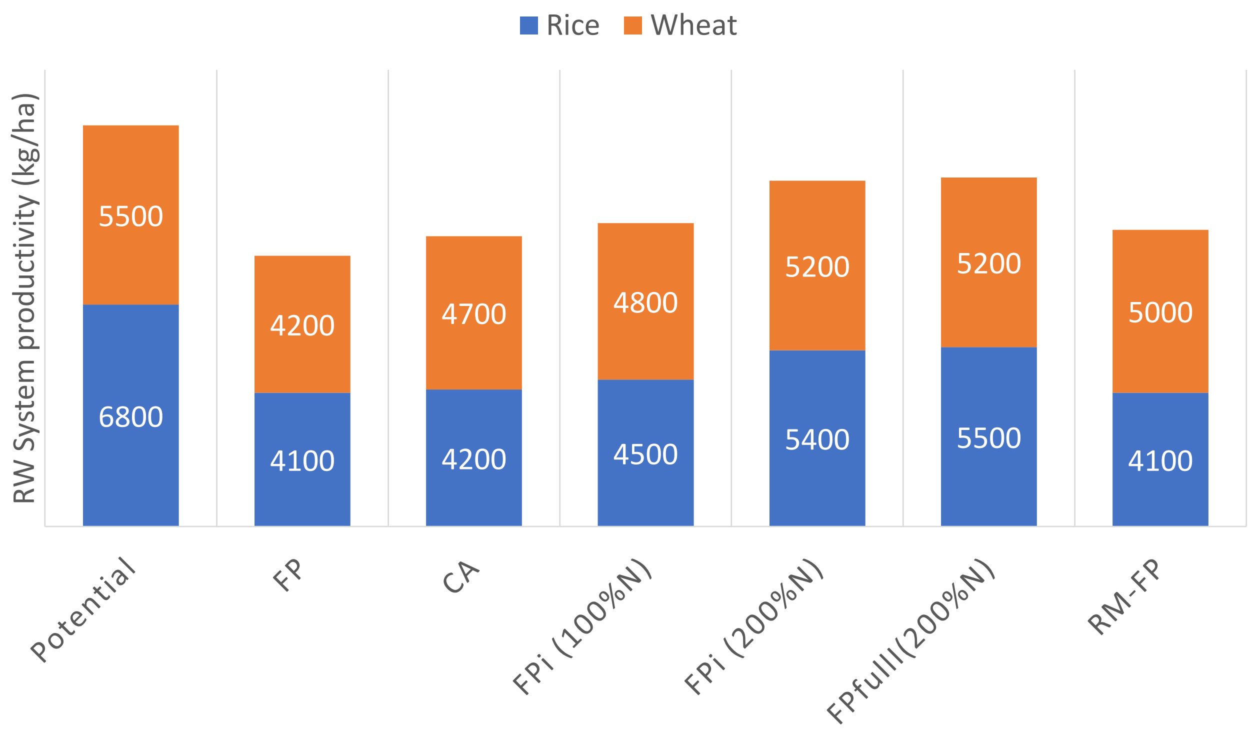

Figure 10. APSIM-simulated productivity of the rice-wheat system in **Varanasi, UP, India** (1987-2017), showing (in addition to those treatments above in figure 9, from left to right) (i) farmer practice + AWD + 100% recommended N; (ii) farmer practice + AWD + 200% recommended N; (iii) farmer production with full irrigation in rice + 200% recommended N; and (iv) rice-maize rotation following farmer practice

3.1.4 Nepalganj, Western Terrai, Nepal

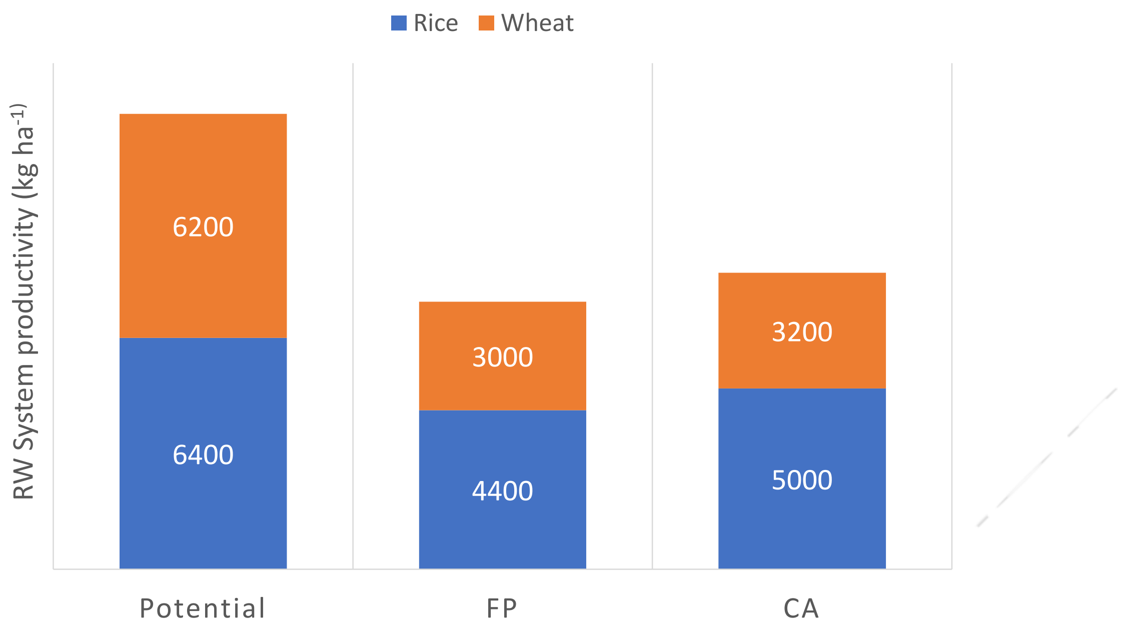

Figure 11. APSIM-simulated productivity of the rice-wheat system in **Nepalganj, Nepal** (1985-2015), showing (from left to right) (i) potential production; (ii) typical farmer practice; (iii) farmer practice following CA principles

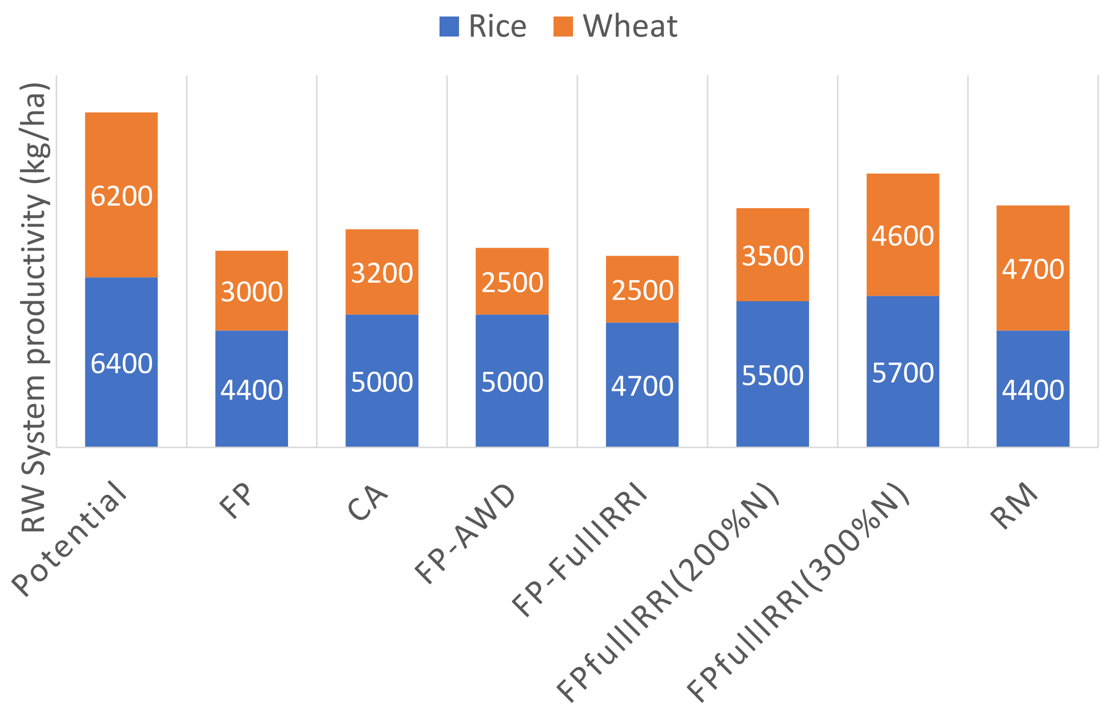

Figure 12. APSIM-simulated productivity of the rice-wheat system in **Nepalganj, Nepal** (1985-2015), showing (in addition to those treatments above in figure 11, from left to right) (i) farmer practice + AWD + 100% recommended N; (ii) farmer practice + AWD + 200% recommended N; (iii) farmer production with full irrigation in rice + 200% recommended N; (iv) farmer production with full irrigation in rice + 300% recommended N; and (v) rice-maize rotation following farmer practice

3.1.5 Tarahara, Sunsari, Nepal

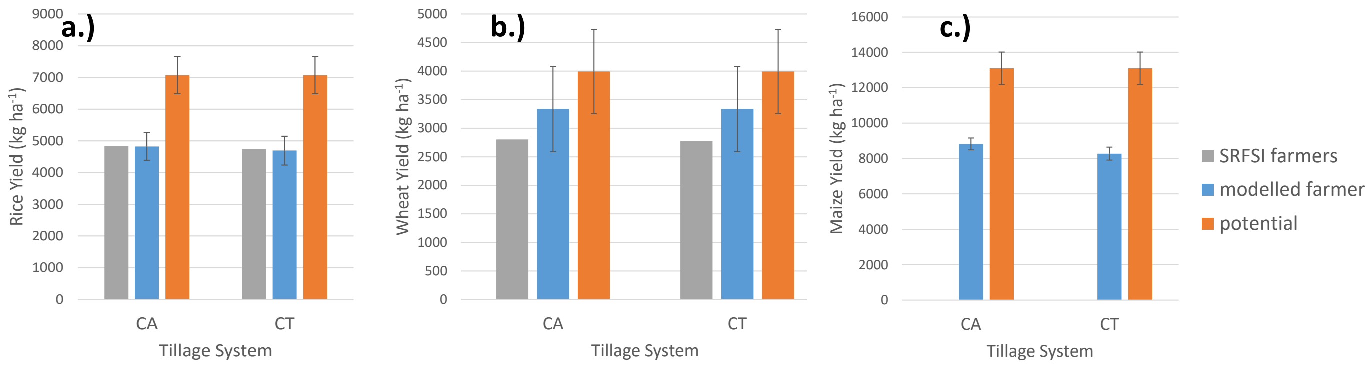

Figure 13. APSIM-simulated productivity of a.) KHARIF RICE, b.) WHEAT, and c.) MAIZE for Sunsari, Nepal (1983-2015), showing physiological potential yields, APSIM-modelled yields, and SRFSI farmer field trial yields for (i) conventional farmer practice (CT) and; (ii) farmer practice following CA principles. Error bars indicate one standard deviation either side of the simulated mean, over the period of simulations.

3.1.6 Patna, Bihar, India

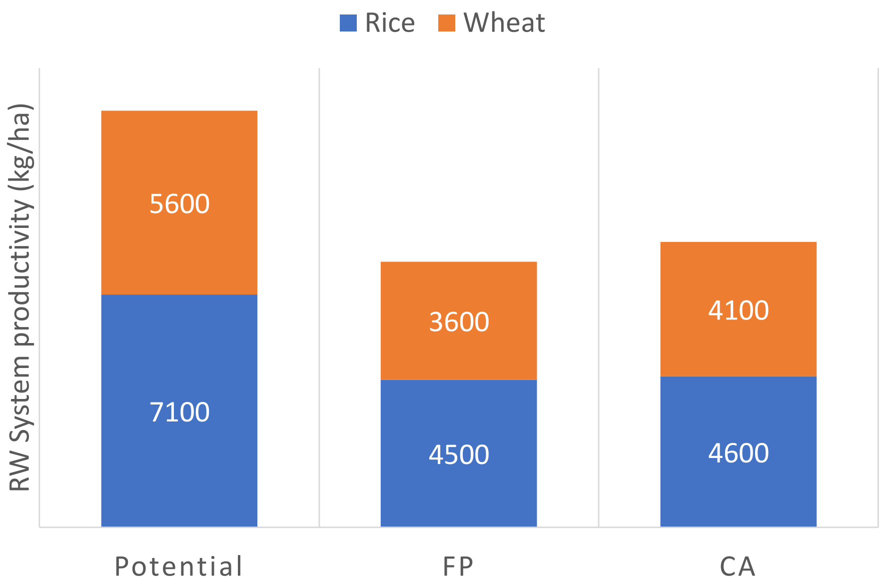

Figure 14. APSIM-simulated productivity of the rice-wheat system in Patna, Bihar, India (1970-2015), showing (from left to right) (i) potential production; (ii) typical farmer practice; (iii) farmer practice following CA principles

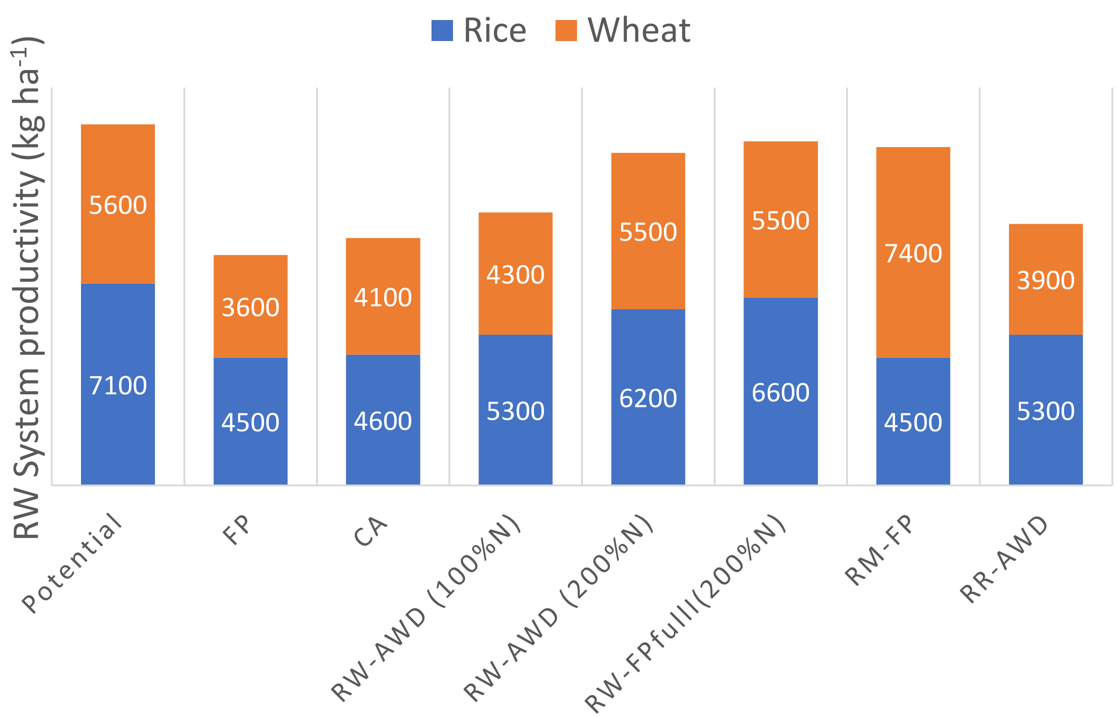

Figure 15. APSIM-simulated productivity of the rice-wheat system in **Patna, Bihar, India** (1970-2015), showing (in addition to those treatments above in figure 14, from left to right) (i) farmer practice + AWD + 100% recommended N; (ii) farmer practice + AWD + 200% recommended N; (iii) farmer production with full irrigation in rice + 200% recommended N; (iv) rice-maize rotation following farmer practice; and (v) rice-rice rotation with AWD

3.1.7 Malda, West Bengal, India

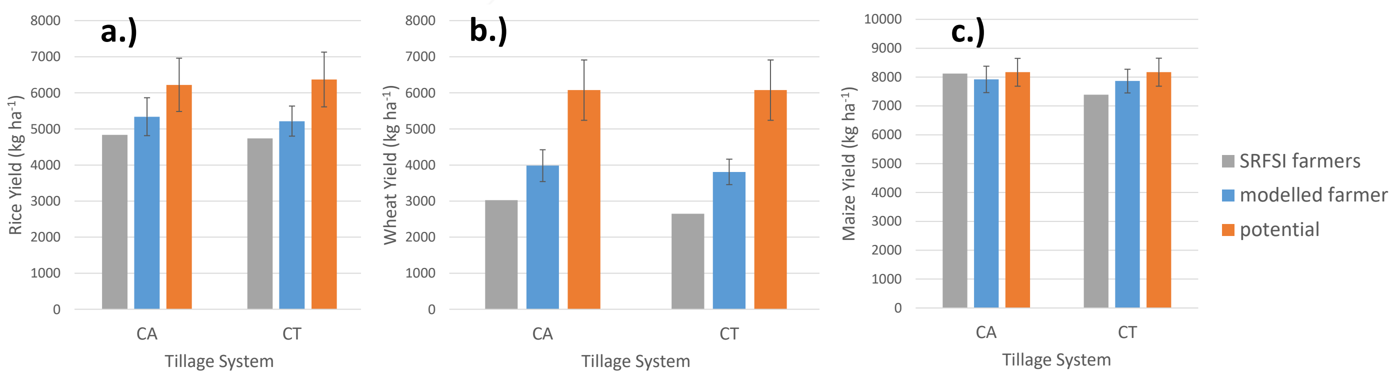

Figure 16. APSIM-simulated productivity of a.) KHARIF RICE, b.) WHEAT, and c.) MAIZE for **Malda, WB, India** (1995-2016), showing physiological potential yields, APSIM-modelled yields, and SRFSI farmer field trial yields for (i) conventional farmer practice (CT) and; (ii) farmer practice following CA principles. Error bars indicate one standard deviation either side of the simulated mean, over the period of simulations.

3.1.8 Coochbehar, West Bengal, India

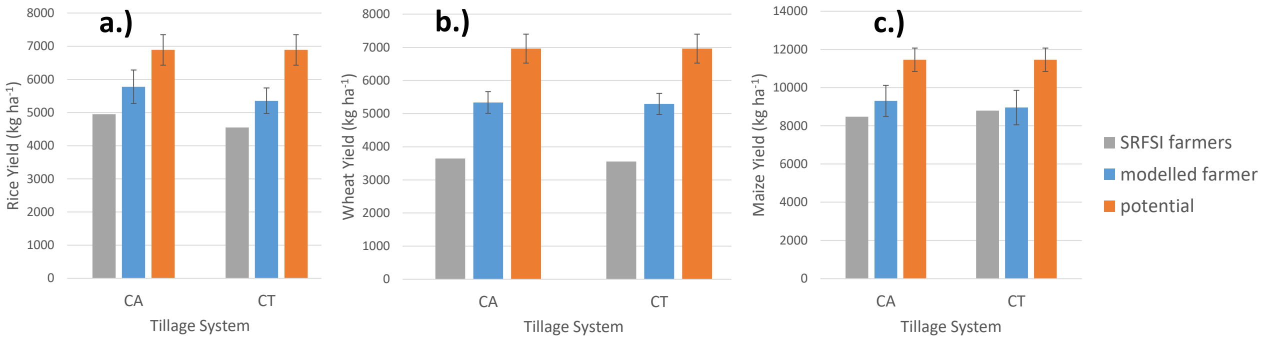

Figure 17. APSIM-simulated productivity of a.) KHARIF RICE, b.) WHEAT, and c.) MAIZE for Coochbehar, WB, India (1996-2016), showing physiological potential yields, APSIM-modelled yields, and SRFSI farmer field trial yields for (i) conventional farmer practice (CT) and; (ii) farmer practice following CA principles. Error bars indicate one standard deviation either side of the simulated mean, over the period of simulations.

3.1.9 Dinajpur, Bangladesh

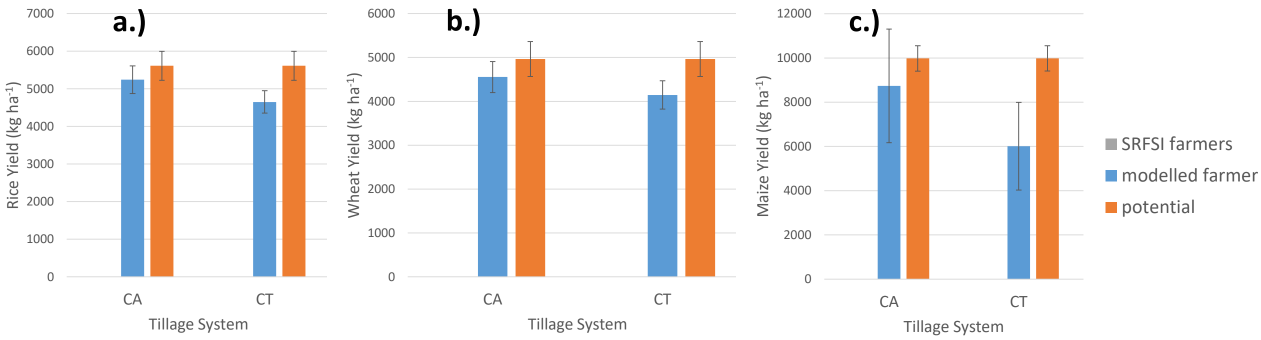

Figure 18. APSIM-simulated productivity of a.) KHARIF RICE, b.) WHEAT, and c.) MAIZE for Dinajpur, Bangladesh (1982-2019), showing physiological potential yields, APSIM-modelled yields, and SRFSI farmer field trial yields for (i) conventional farmer practice (CT) and; (ii) farmer practice following CA principles. Error bars indicate one standard deviation either side of the simulated mean, over the period of simulations.

3.1.10 Rajshahi, Bangladesh

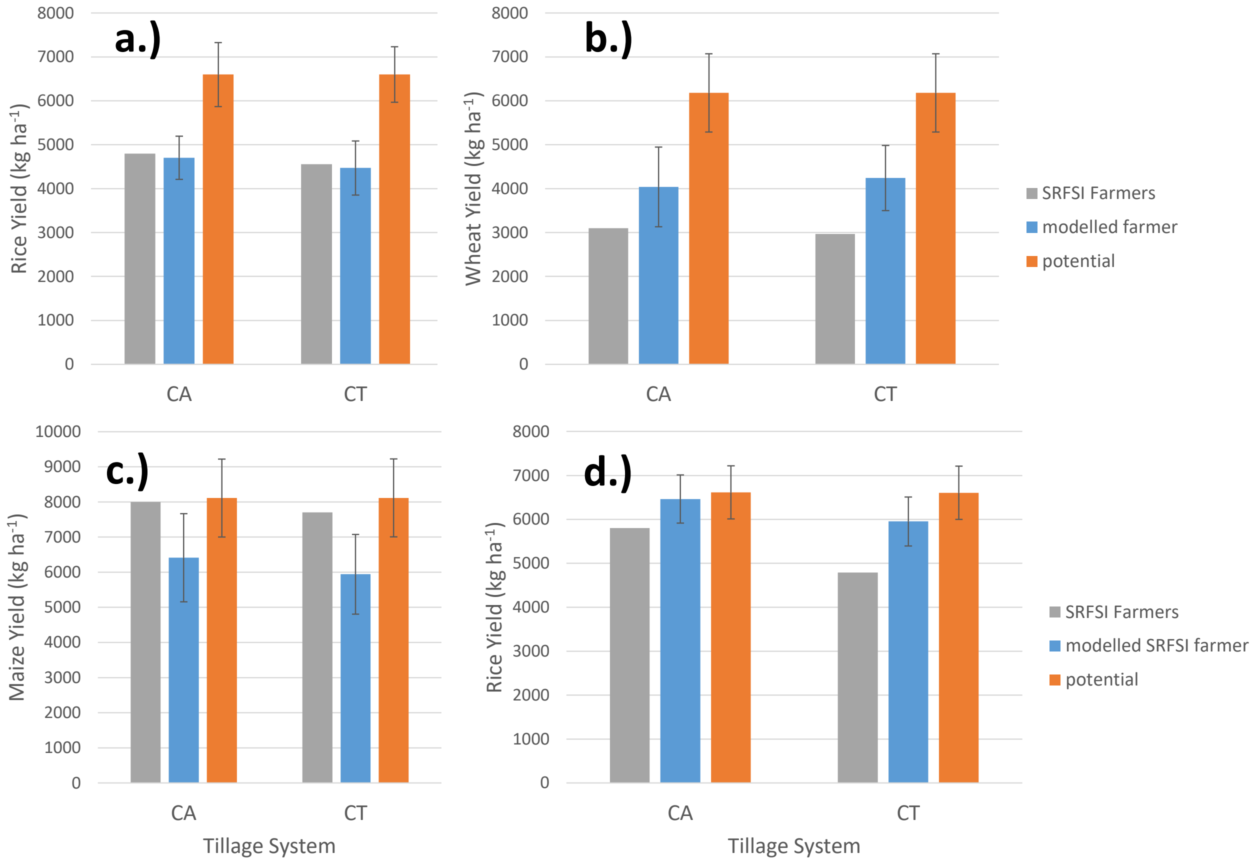

Figure 19. APSIM-simulated productivity of a.) KHARIF RICE, b.) WHEAT, c.) MAIZE, and d.) BORO RICE for Rajshahi, Bangladesh (1983-2017), showing physiological potential yields, APSIM-modelled yields, and SRFSI farmer field trial yields for (i) conventional farmer practice (CT) and; (ii) farmer practice following CA principles. Error bars indicate one standard deviation either side of the simulated mean, over the period of simulations.

3.2 Economic Yield Gaps

3.2.1 Summary of Economic Yield Gaps across the IGP

We compared APSIM-simulated farmer practice R-W system gross margins (GMs) for both CT and CA practices, for increasing inputs of fertiliser N. APSIM automatically increased irrigation requirements as needed and also included this in the GM calculations, in addition to the cost of the additional N. This was done to examine how profitability of the cropping system changed as the farmers approached physiological potential yield by increasing inputs. As can be seen in following figures, grain yields for maximising gross margin is often less than maximum grain yield.

At each site, as available data permitted, we determined the fertiliser N inputs required to achieve maximum gross margin and then determined the grain yields for both rice and wheat which were associated with this point of maximum GM. This allowed us to compare these yields with the current farmer yields to make an estimate of the *Economic Yield Gap* in these systems. This was in many cases less than the potential yield gap – in other words, system profit was maximised before the farmers reached the maximum physiological grain yields. We also quantified the associated Gross Margin Gap, defined as the maximum gross margin minus the current farmer gross margin. We considered maximising gross margin by just increasing fertiliser N and associated irrigation, but also by first implementing CA practices and then incrementally increasing fertiliser N and irrigation. These are both detailed below (Table 2)

Summary of our findings across sites is presented in Figures 20-21 and Tables 2-3.

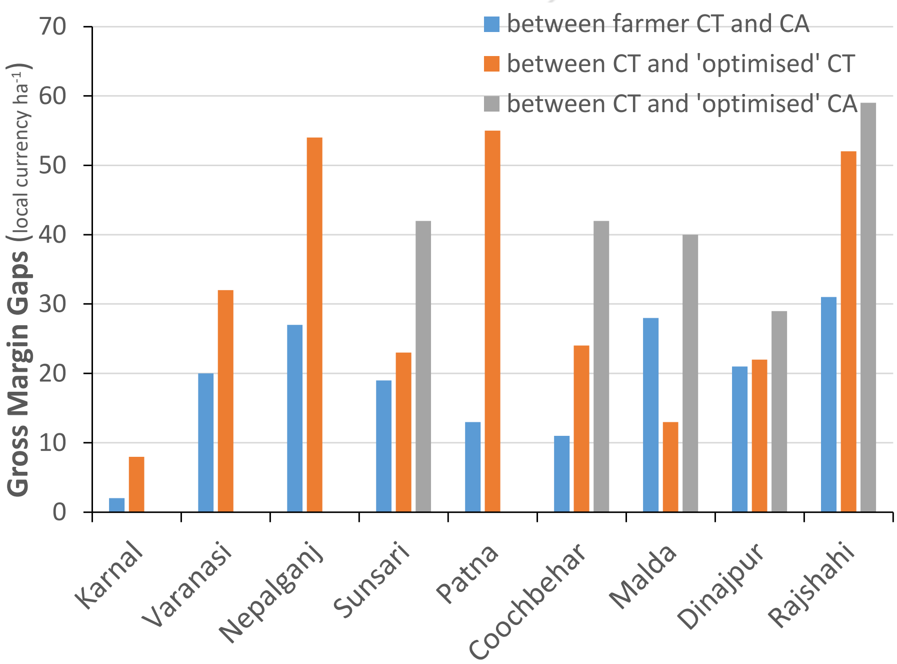

Figure 20. Gross Margin Gaps (GMG) (expressed as a percentage of CT farmer GMs) for the IGP sites examined in this analysis for the R-W system. The impact of implementing CA tillage practices is indicated by the blue (CT) bars. The impact of optimising fertiliser N and irrigation within CT practice is shown by the orange bars, while grey bars illustrate the impact of implementing CA practices and optimising N and irrigation. All figures are simulated using APSIM.

Table 2. Gross Margin Gaps (GMG expressed in local currency ha^{-1})) for the rice-wheat system across the IGP sites, together with the economic yield gap (YG_{econ}) between current farmer yields and the optimum economic yields (CA + optimum fertiliser and irrigation application).

	Gross Margin (in local currency ha^{-1})		Goss Margin Gap (in local currency ha^{-1}) (% of farmer GM)		
Site	Current CT (farmer)	Current CA	Between CT and CA	Between CT and optimised CT system	Between CT and optimised CA system
Karnal	105500	113200	7700 (7%)	8500 (8%)	no data
Varanasi	70700	85000	14300 (20%)	22800 (32%)	no data
Nepalganj	47800	60500	12700 (27%)	25900 (54%)	no data
Sunsari	126112	149587	23475 (19%)	28834 (23%)	53034 (42%)
Patna	87000	98000	11000 (13%)	48000 (55%)	no data
Coochbehar	115205	128060	12855 (11%)	28138 (24%)	48358 (42%)
Malda	95779	122761	26982 (28%)	12743 (13%)	37912 (40%)
Dinajpur	104829	126505	21645 (21%)	23335 (22%)	29900 (29%)
Rajshahi	69992	91474	21482 (31%)	36541 (52%)	41295 (59%)

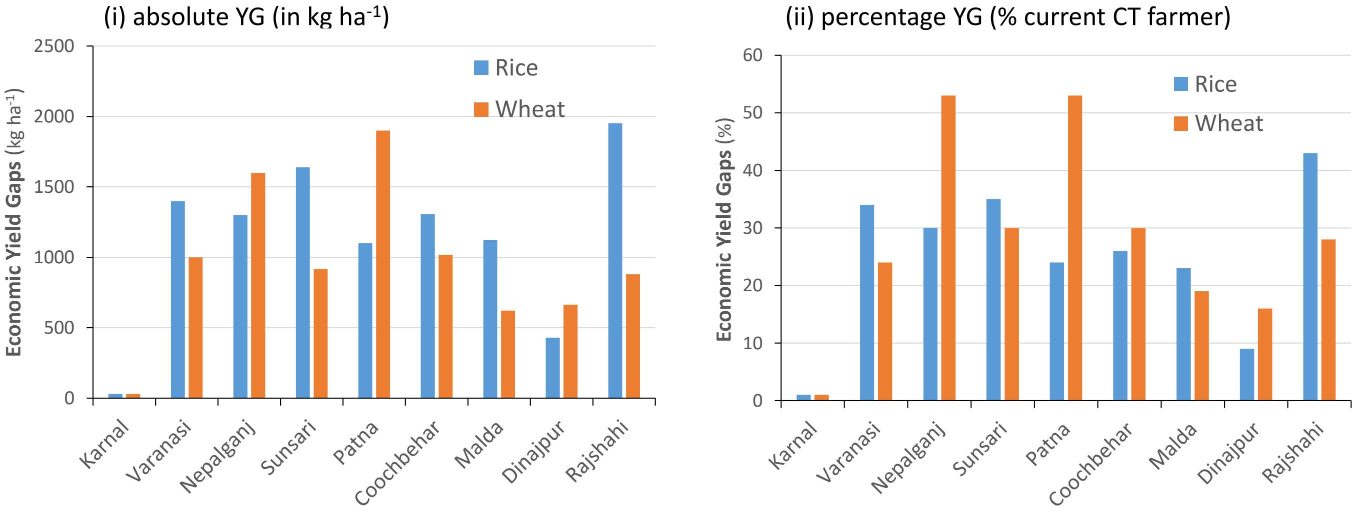

Figure 21. Economic crop yield gaps ((i) in absolute terms (kg ha^{-1}) and (ii) as a percentage of CT farmer yield) for the IGP sites examined in this analysis for the R-W system. These are the yield gaps between what CT farmers are currently achieving, and what they could achieve with optimised GM's under CT practice (increasing fertiliser N and required irrigation until GM's are maximised and begin to decline). All figures are simulated using APSIM.

Site	Variable	RICE				WHEAT			
		Grain Yield (kg ha^{-1})	N fertiliser multiplier	YG_{econ} (kg ha^{-1})	YG_{econ} (%)	Grain Yield (kg ha^{-1})	N fertiliser multiplier	YG_{econ} (kg ha^{-1})	YG_{econ} (%)
Karnal	farmer CT optimum GM (CT) optimum GM (CA)	6400 6400 6400	1.0 1.0	0 0	0 0	5500 5500 5500	1.0 1.0	0 0	0 0
Varanasi	farmer CT optimum GM (CT) optimum GM (CA)	4100 5500 no data	2.0 No data	1400 No data	34 No data	4200 5200 No data	2.0 No data	1000 No data	24 no data
Nepalganj	farmer CT optimum GM (CT) optimum GM (CA)	4400 5700 no data	3.0 No data	1300 No data	30 no data	3000 4600 no data	3.0 No data	1600 No data	53 no data
Sunsari	farmer CT optimum GM (CT) optimum GM (CA)	4713 6352 6620	2.7 2.7	1639 1907	35 40	3080 3997 3997	1.4 1.0	917 917	30 30
Patna	farmer CT optimum GM (CT) optimum GM (CA)	4500 6600 no data	2.0 No data	1100 No data	24 no data	3600 5500 no data	2.0 No data	1900 No data	53 No data
Coochbehar	farmer CT optimum GM (CT) optimum GM (CA)	5089 6396 6497	- 2.7 2.7	- 1307 1407	26 28	3420 4439 4456	1.6 1.4	1019 1036	30 30
Malda	farmer CT optimum GM (CT) optimum GM (CA)	4894 6017 5933	2.1 1.75	1123 1039	23 21	3350 3972 4391	1.0 1.4	622 1040	19 11

Dinajpur	farmer CT optimum GM (CT) optimum GM (CA)	4536 4967 5320	1.7 1.4	430.6 784.1	9.0 17	4127 4792 4796	1.7 1.4	665 668	16 16
Rajshahi	farmer CT optimum GM (CT) optimum GM (CA)	4500 6453 6642	2.7 2.5	1953 1788	43 47	3140 4020 4020	1.3 1.5	880 880	28 28

Table 3. *Economic Yield Gap* (YG_{econ}, expressed in kg ha^{-1})) between current farmer (CT) yields and the optimum economic yields (both CT and CA, plus optimum fertiliser and irrigation application) for the rice-wheat system across the IGP sites to achieve maximal gross margin (Table YY).

Specific details on individual sites are provided in the following sections.

3.2.2 Karnal, Haryana, India

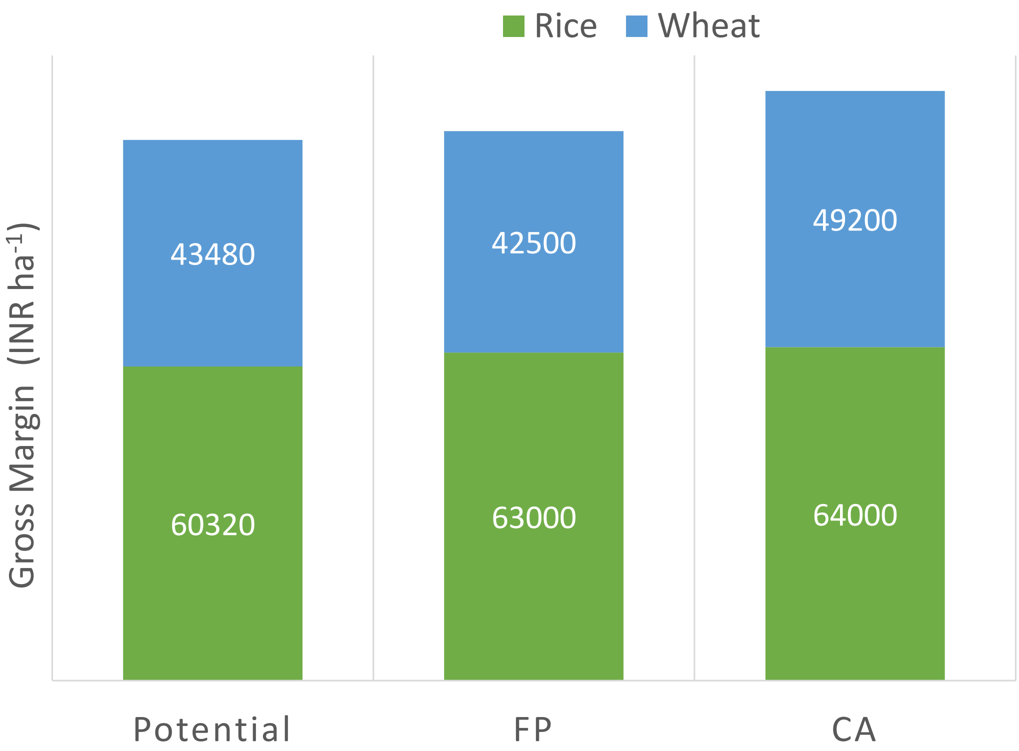

Figure 22. APSIM-simulated Gross Margins (GM – in Indian Rupees (INR)) of the rice-wheat system in Karnal, Haryana, India (1984-2018) with existing electricity subsidy, showing (from left to right) (i) potential production; (ii) typical farmer production; (iii) farmer production following CA principles.

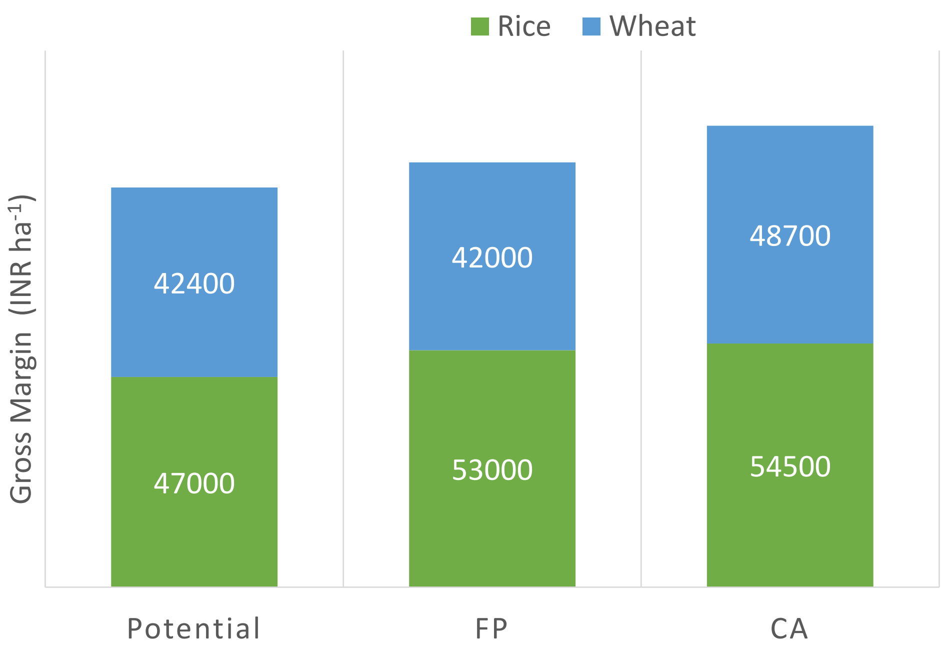

Figure 23. APSIM-simulated Gross Margins (GM – in Indian Rupees (INR)) of the rice-wheat system in **Karnal, Haryana, India** (1984-2018) **without** existing electricity subsidy, showing (from left to right) (i) potential production; (ii) typical farmer production; (iii) farmer production following CA principles.

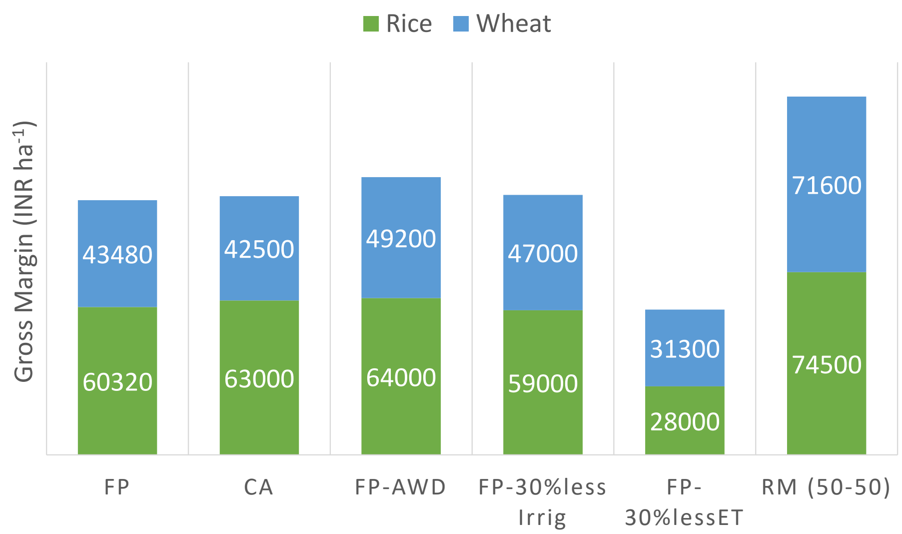

Figure 24. APSIM-simulated Gross Margins (GM – in Indian Rupees (INR)) of the rice-wheat system in **Karnal, Haryana, India** (1984-2018) **with** existing electricity subsidy, showing (in addition to those treatments above in figure 22, from left to right) (i) farmer practice + AWD; (ii) farmer practice with 30% reduction in irrigation for rice; (iii) farmer production with 30% reduction in ET for rice; and (iv) a 50-50 rice-maize mix in the kharif, following farmer practice, with 100% wheat in Rabi.

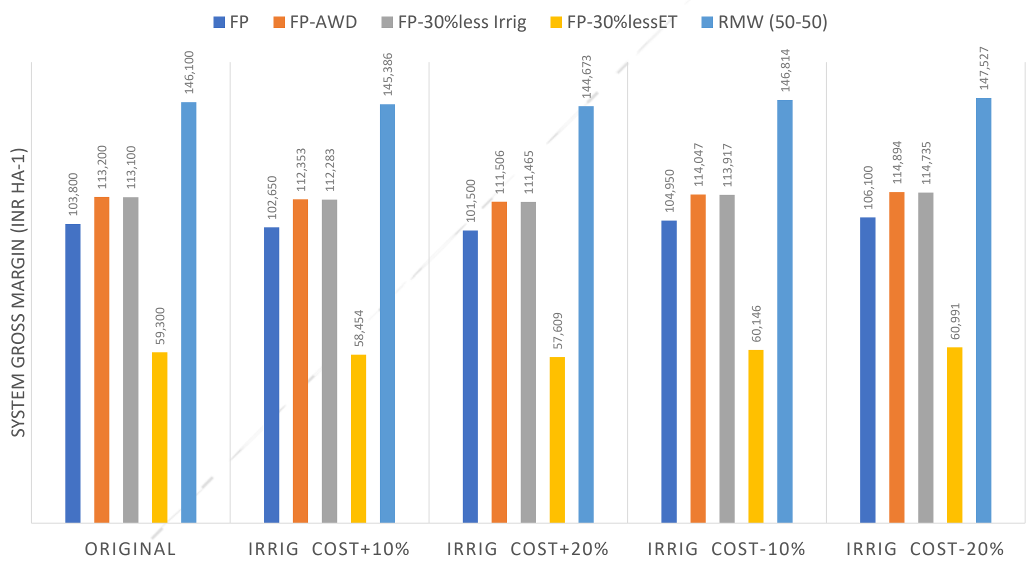

Figure 25. APSIM-simulated Gross Margins (GM – in Indian Rupees (INR)) of the rice-wheat system in **Karnal, Haryana, India** (1984-2018), showing the impact of +/- 10% and +/- 20% changes in cost of irrigation for several different cropping system options from left to right) (i) farmer practice + AWD; (ii) farmer practice with 30% reduction in irrigation for rice; (iii) farmer production with 30% reduction in ET for rice; and (iv) a 50-50 rice-maize mix in the kharif, following farmer practice, with 100% wheat in Rabi.

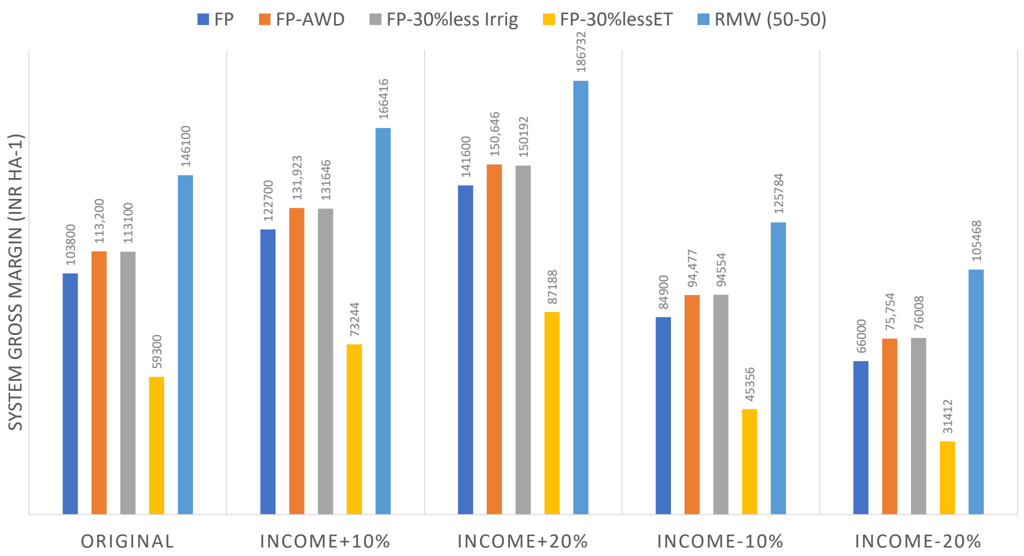

Figure 26. APSIM-simulated Gross Margins (GM – in Indian Rupees (INR)) of the rice-wheat system in **Karnal, Haryana, India** (1984-2018), showing the impact of +/- 10% and +/- 20% changes in grain price for several different cropping system options from left to right) (i) farmer practice + AWD; (ii) farmer practice with 30% reduction in irrigation for rice; (iii) farmer production with 30% reduction in ET for rice; and (iv) a 50-50 rice-maize mix in the kharif, following farmer practice, with 100% wheat in Rabi..

3.2.3 Varanasi, UP, India

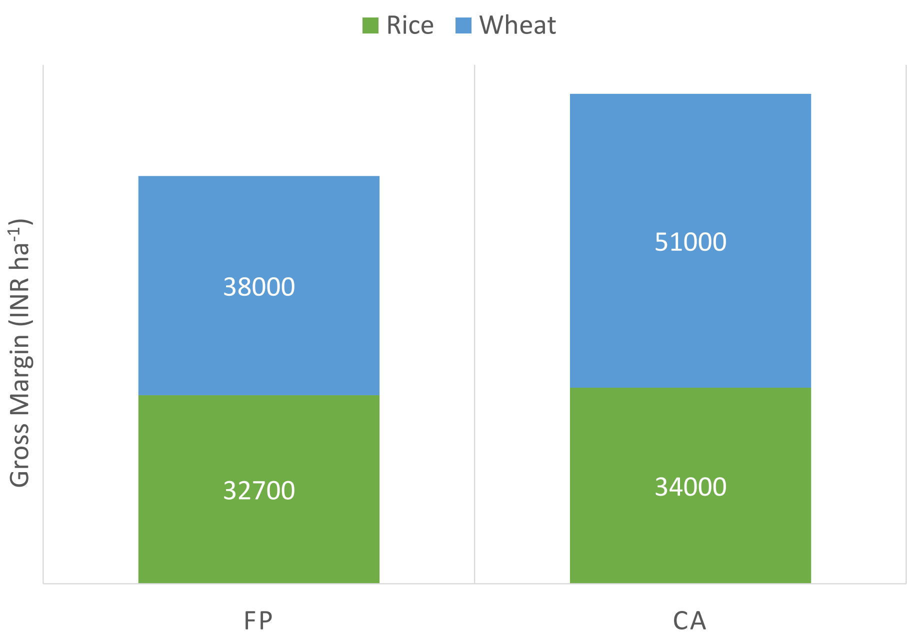

Figure 27. APSIM-simulated Gross Margins (GM – in Indian Rupees (INR)) of the rice-wheat system in **Varanasi, UP, India** (1987-2017), showing (from left to right) (i) typical farmer production (FP); and (ii) farmer production following CA principles.

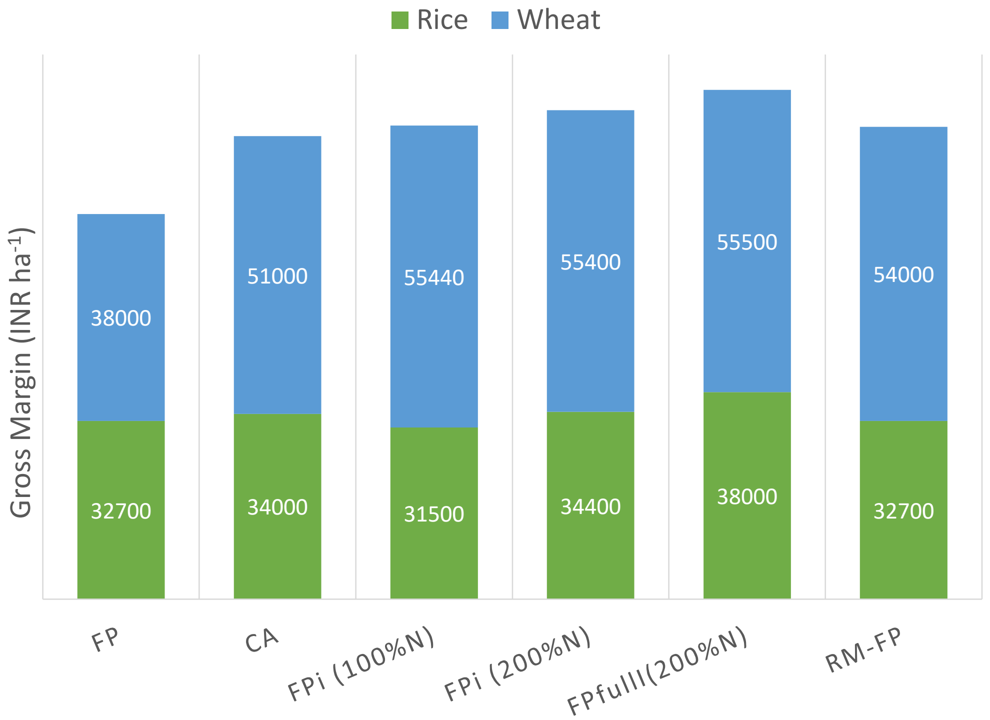

Figure 28. APSIM-simulated Gross Margins (GM – in Indian Rupees (INR)) of the rice-wheat system in **Varanasi, UP, India** (1987-2017), showing (in addition to those treatments above in figure 27, from left to right) (i) farmer practice + AWD + 100% recommended N; (ii) farmer practice + AWD + 200% recommended N; (iii) farmer production with full irrigation in rice + 200% recommended N; and (iv) rice-maize rotation following farmer practice

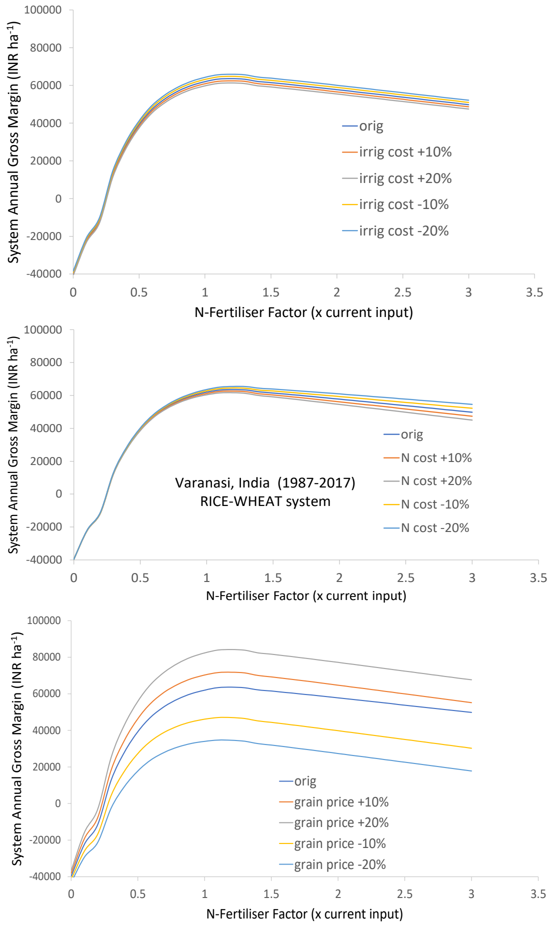

Figure 29. APSIM-simulated Gross Margins (GM – in Indian Rupees (INR)) of the rice-wheat system in **Varanasi, UP, India** (1987-2017), showing the impact of +/- 10% and +/- 20% changes in (i) cost of irrigation; (ii) cost of fertiliser N; and (iii) grain price

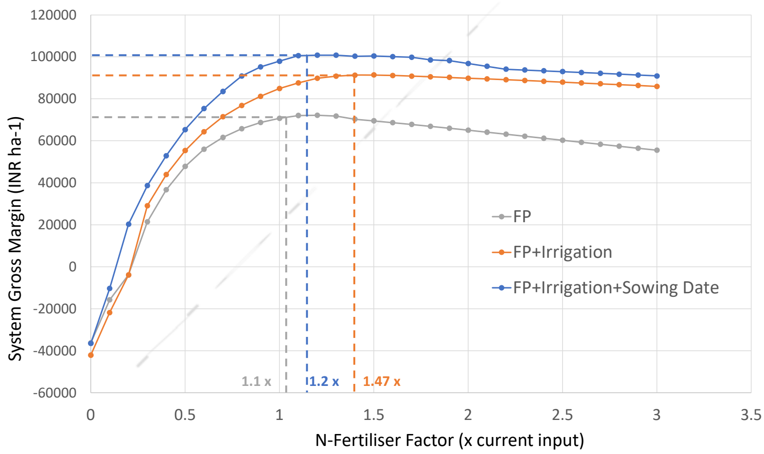

Figure 30. APSIM-simulated Gross Margins (GM – in Indian Rupees (INR)) of the rice-wheat system in **Varanasi, UP, India** (1987-2017), showing the variation of optimal N-rate and possible farmer returns (gross margins) with changes in management practice.

3.2.4 Nepalganj, Western Terrai, Nepal

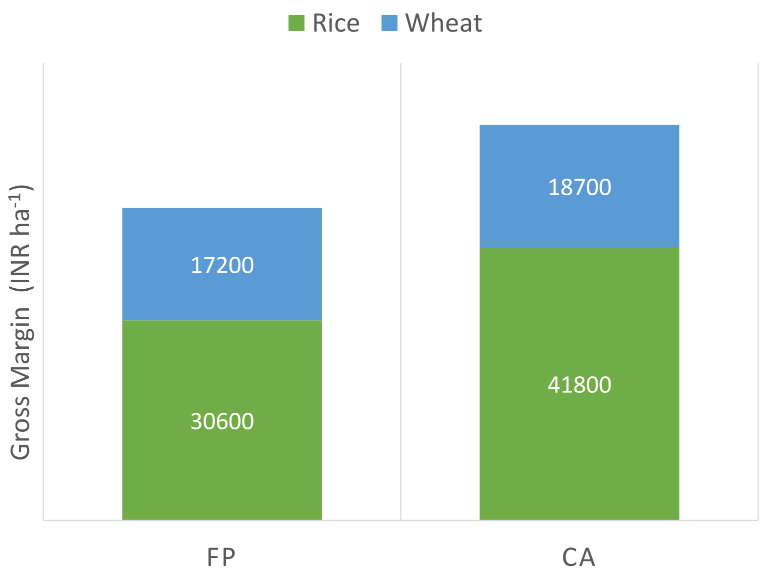

Figure 31. APSIM-simulated Gross Margins (GM – in Nepali Rupees (INR)) of the rice-wheat system in **Nepalganj, Nepal (1985-2015)**, showing (from left to right) (i) potential production; (ii) typical farmer production; (iii) farmer production following CA principles.

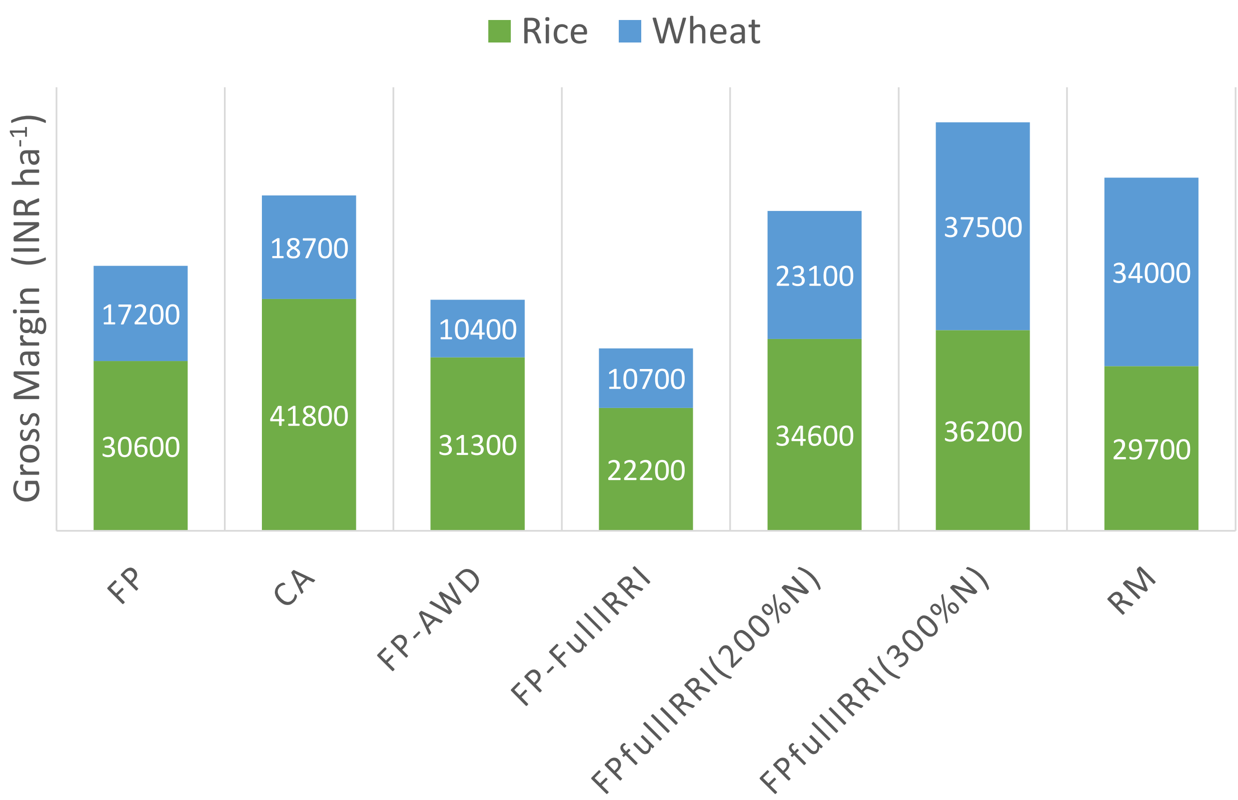

Figure 32. APSIM-simulated Gross Margins (GM – in Nepali Rupees (INR)) of the rice-wheat system in **Nepalganj, Nepal (1985-2015)**, showing (in addition to those treatments above in figure 31, from left to right) (i) farmer practice + AWD + 100% recommended N; (ii) farmer practice + AWD + 200% recommended N; (iii) farmer production with full irrigation in rice + 200% recommended N; (iv) farmer production with full irrigation in rice + 300% recommended N; and (v) rice-maize rotation following farmer practice

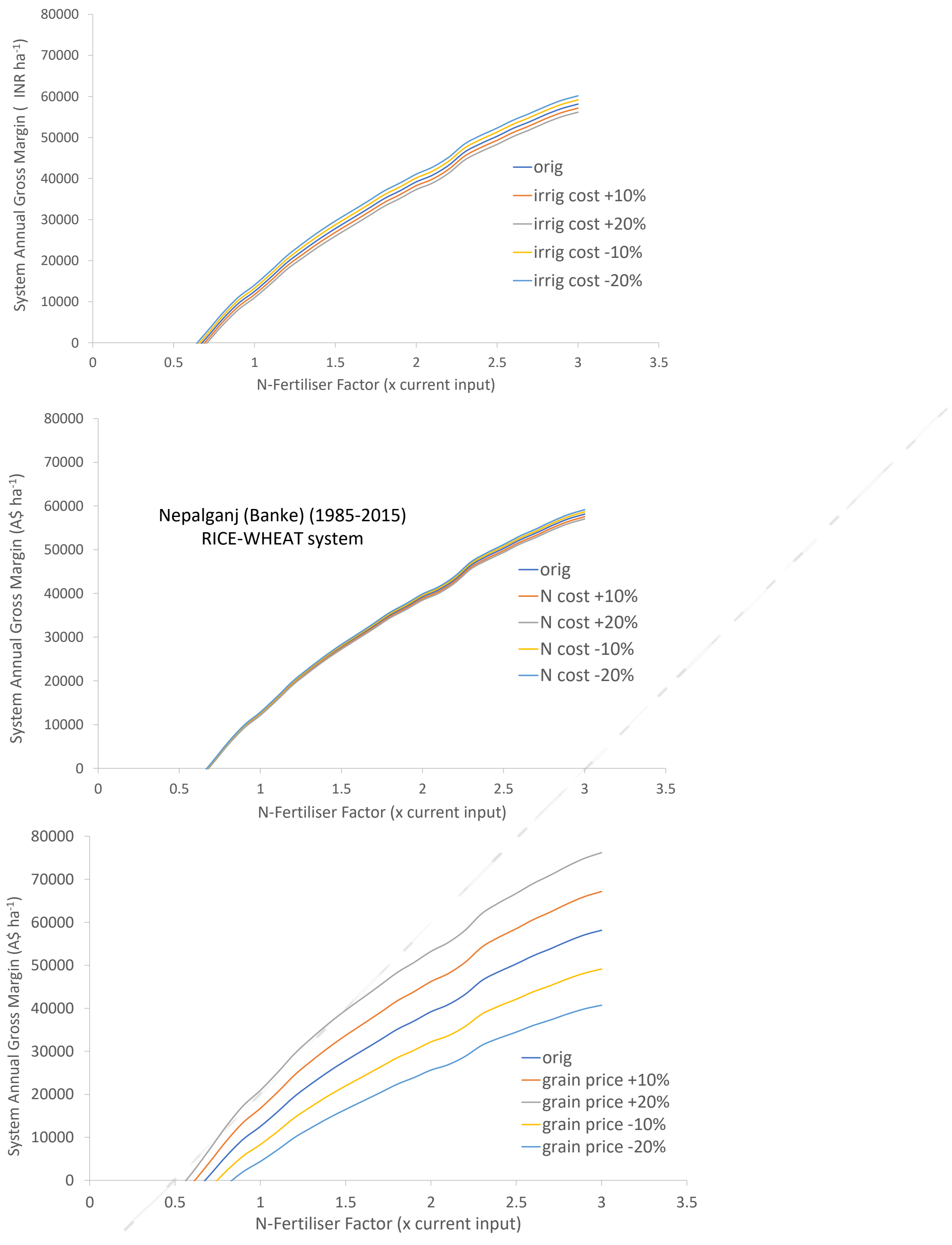

Figure 33. APSIM-simulated Gross Margins (GM – in Nepali Rupees (INR)) of the rice-wheat system in **Nepalganj, Nepal (1985-2015)**, showing the impact of +/- 10% and +/- 20% changes in (i) cost of irrigation; (ii) cost of fertiliser N; and (iii) grain price

3.2.5 Tarahara, Sunsari, Nepal

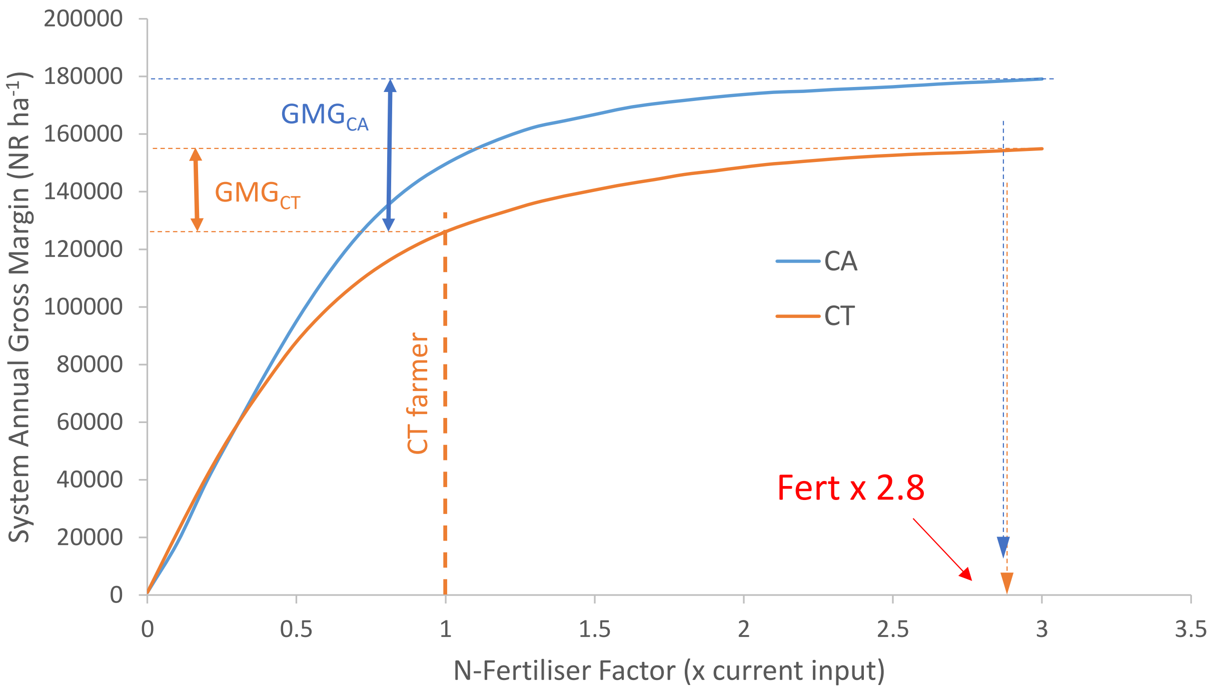

Figure 34. APSIM-simulated Gross Margins (GM – in Nepalese Rupees) of the rice-wheat system in **Tarahara, Sunsari, Nepal (1991-2016)**, showing the variation of optimal N-rate and possible farmer returns (gross margins) with changes in management practice (CA vs CT). The **GMG**$_{CT}$ is the gross margin gap between current farmer and the optimal CT fertiliser and irrigation practice, whereas the **GMG**$_{CA}$ is the gross margin gap between current farmer CT practice, and the optimal CA practice. The fertiliser multiplication factor required to reach each of these is indicated in RED

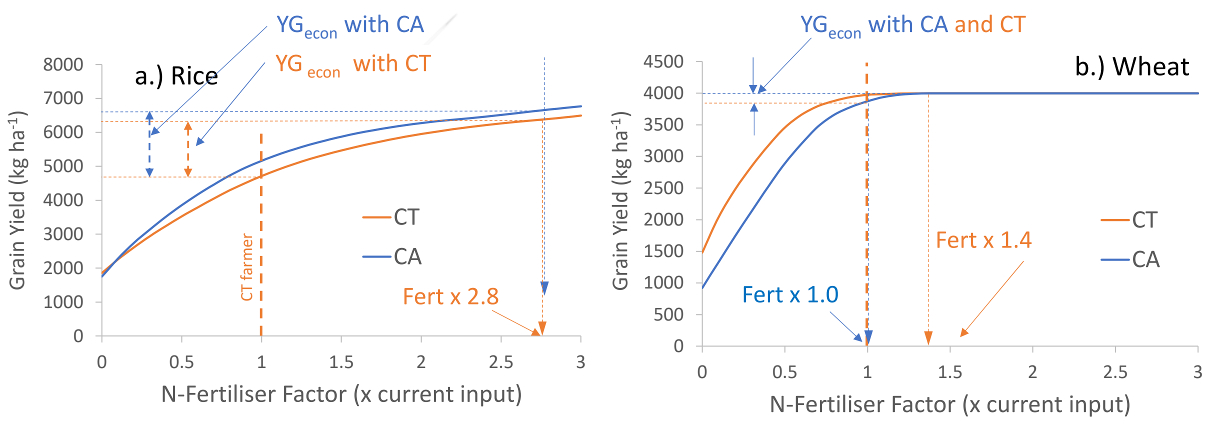

Figure 35. APSIM-simulated yields for a.) rice and b.) wheat (kg ha^{-1}) in **Tarahara, Sunsari, Nepal (1991-2016)**, showing the yields achieved using the optimal fertiliser rates for both CT and CA practice (from Figure 34), and the resultant crop economic yield gaps.

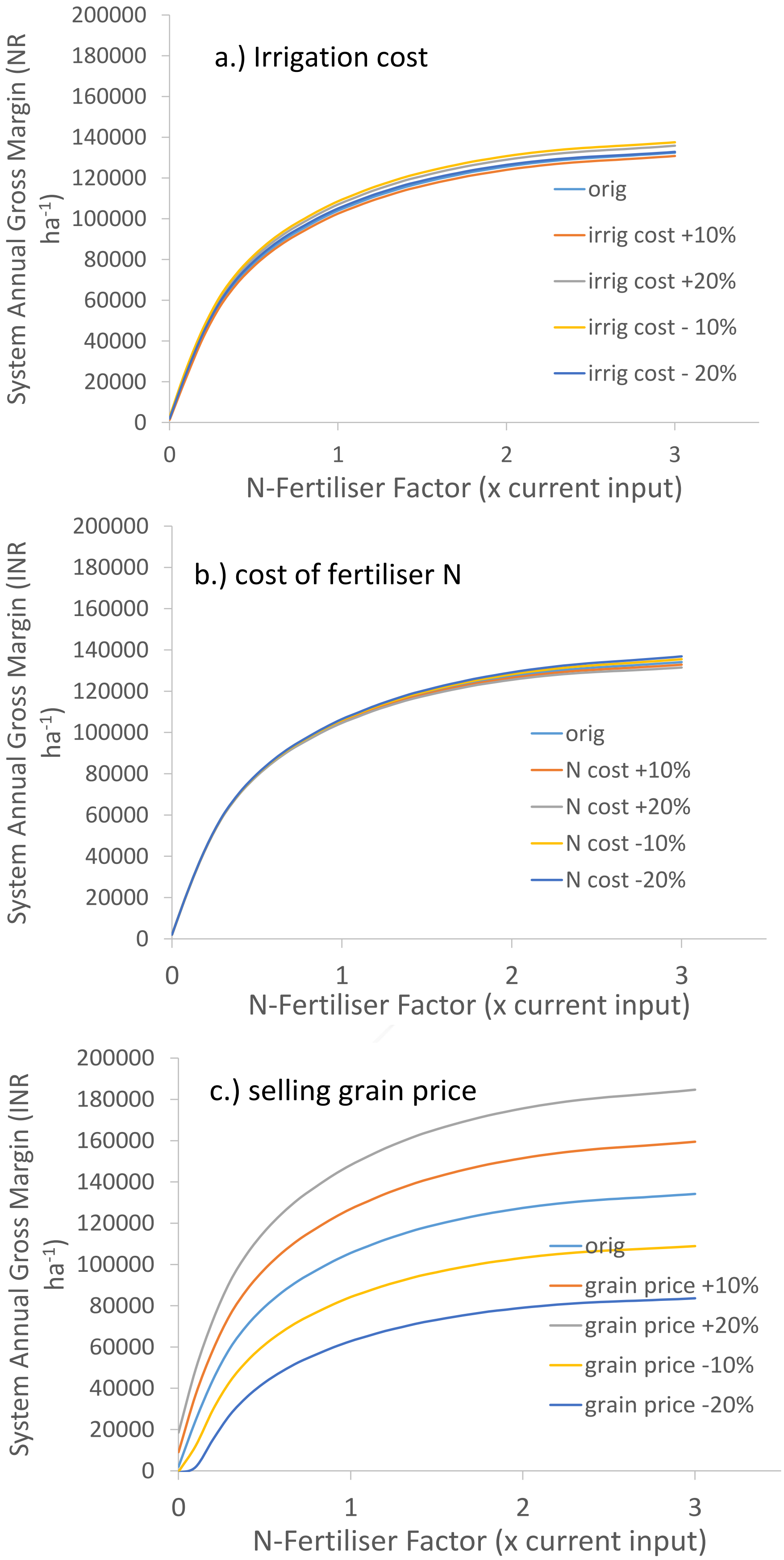

Figure 36. Sensitivity of APSIM-simulated GMs for the CT rice-wheat system (GM – in Nepali Rupees) in Tarahara, Sunsari, Nepal (1991-2016), to +/- 10% and +/- 20% changes in (a) cost of irrigation; (b) cost of N fertiliser; and (c) selling price of grain.

3.2.6 Patna, Bihar, India

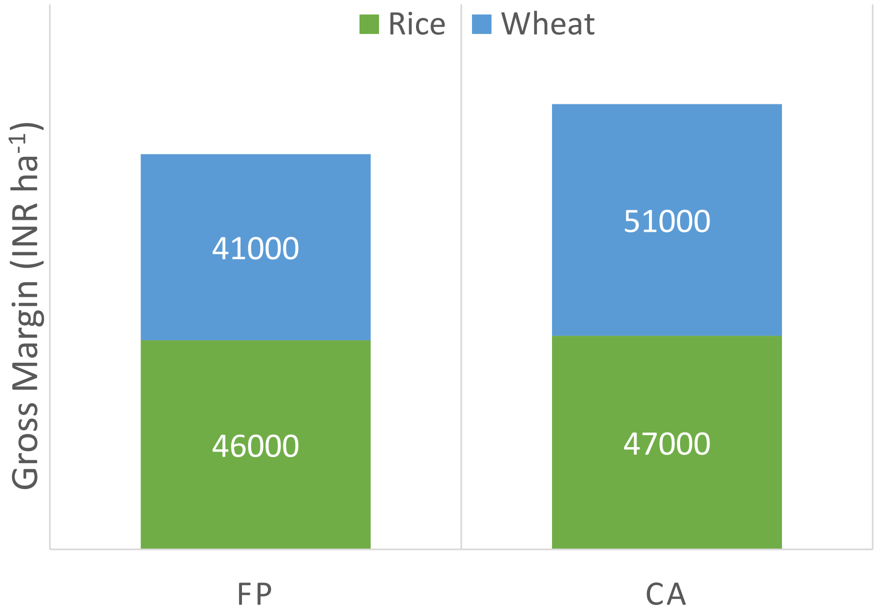

Figure 37. APSIM-simulated Gross Margins (GM – in Indian Rupees (INR)) of the rice-wheat system in **Patna, Bihar, India** (1970-2015), showing (from left to right) (i) potential production; (ii) typical farmer production; (iii) farmer production following CA principles.

Figure 38. APSIM-simulated Gross Margins (GM – in Indian Rupees (INR)) of the rice-wheat system in **Patna, Bihar, India** (1970-2015), showing (in addition to those treatments above in figure 37, from left to right) (i) farmer practice + AWD + 100% recommended N; (ii) farmer practice + AWD + 200% recommended N; (iii) farmer production with full irrigation in rice + 200% recommended N; and (iv) rice-maize rotation following farmer practice.

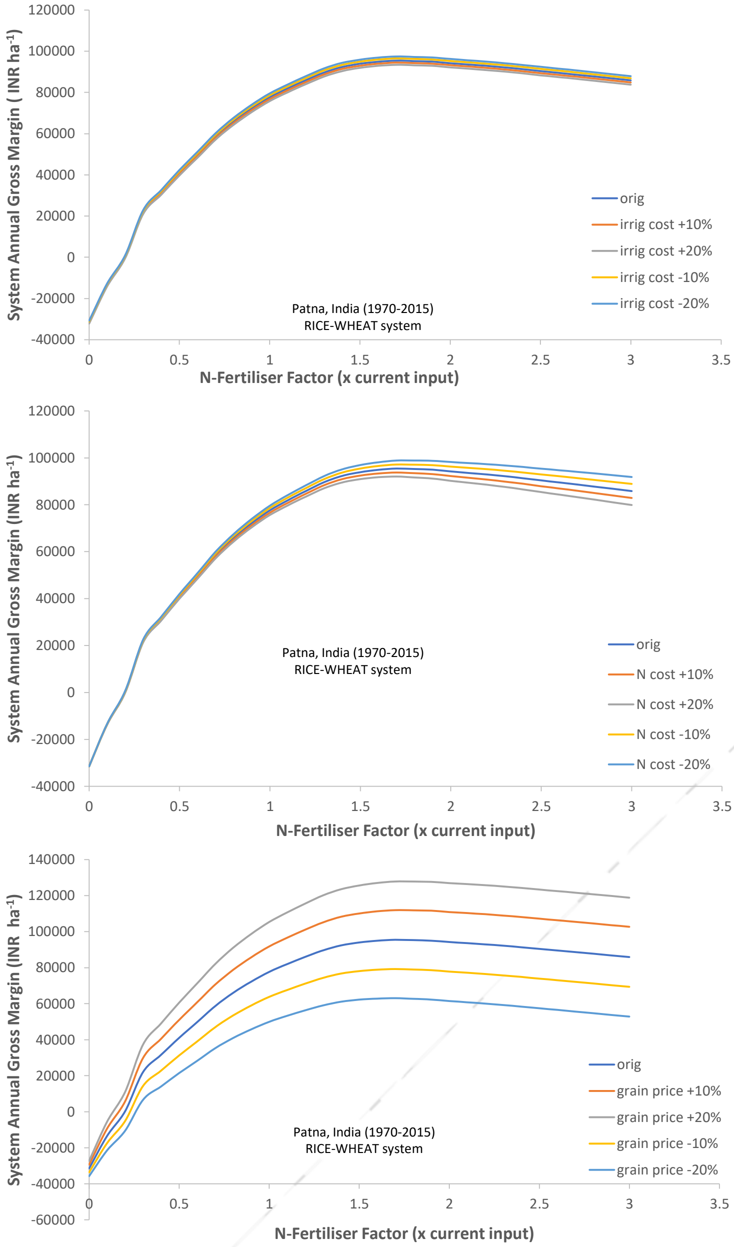

Figure 39. APSIM-simulated Gross Margins (GM – in Indian Rupees (INR)) of the rice-wheat system in **Patna, Bihar, India** (1970-2015), showing the impact of +/- 10% and +/- 20% changes in (a) cost of irrigation; (b) cost of N fertiliser; and (c) selling price of grain.

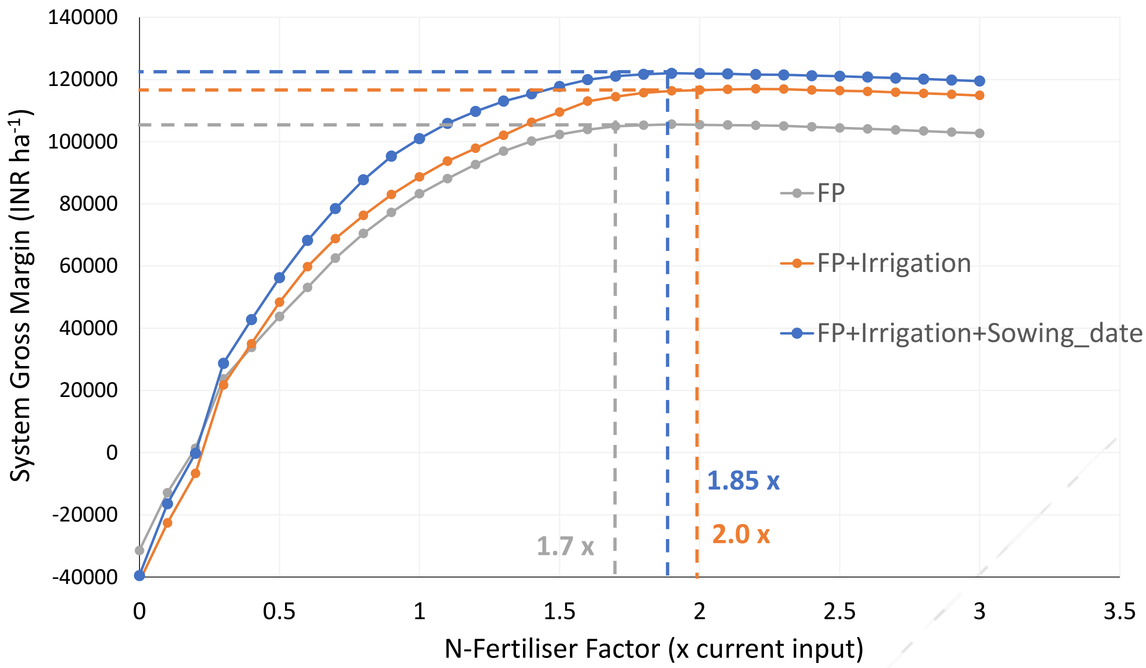

Figure 40. APSIM-simulated Gross Margins (GM – in Indian Rupees (INR)) of the rice-wheat system in **Patna, Bihar, India** (1970-2015), showing the variation of optimal N-rate and possible farmer returns (gross margins) with changes in management practice.

3.2.7 Malda, West Bengal, India

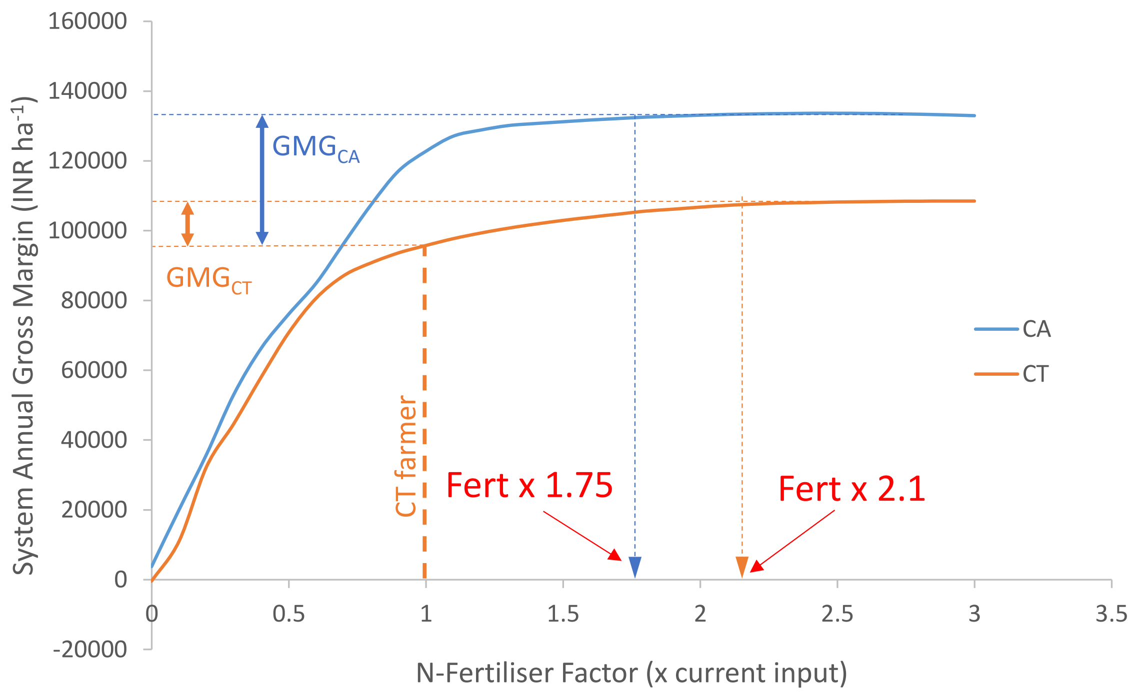

Figure 41. APSIM-simulated Gross Margins (GM – in Indian Rupees, INR) of the rice-wheat system in **Malda, West Bengal (1995-2017)**, showing the variation of optimal N-rate and possible farmer returns (gross margins) with changes in management practice (CA vs CT). The GMG_{CT} is the gross margin gap between current farmer and the optimal CT fertiliser and irrigation practice, whereas the GMG_{CA} is the gross margin

gap between current farmer CT practice, and the optimal CA practice. The fertiliser multiplication factor required to reach each of these is indicated in RED

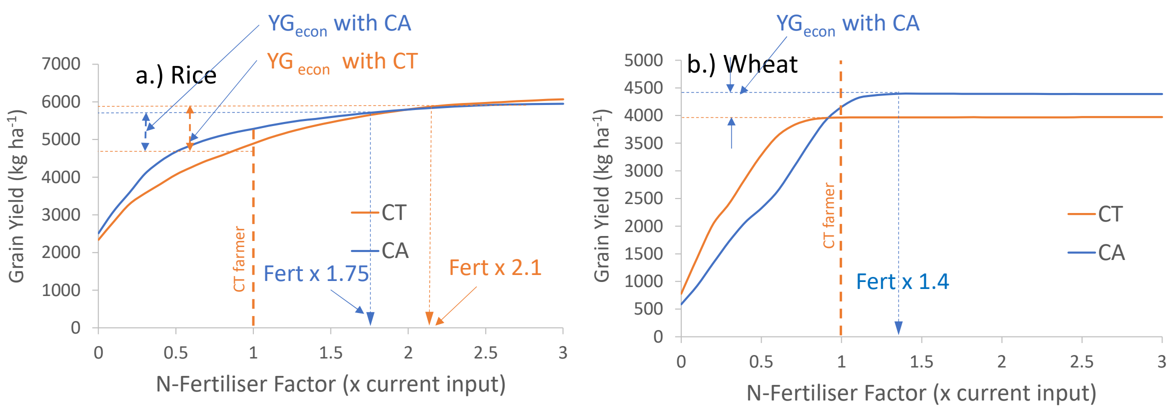

Figure 42. APSIM-simulated yields for rice and wheat (kg ha^{-1}) in Malda, West Bengal (1995-2017), showing the yields achieved using the optimal fertiliser rates for both CT and CA practice (from Figure 41), and the resultant crop economic yield gaps.

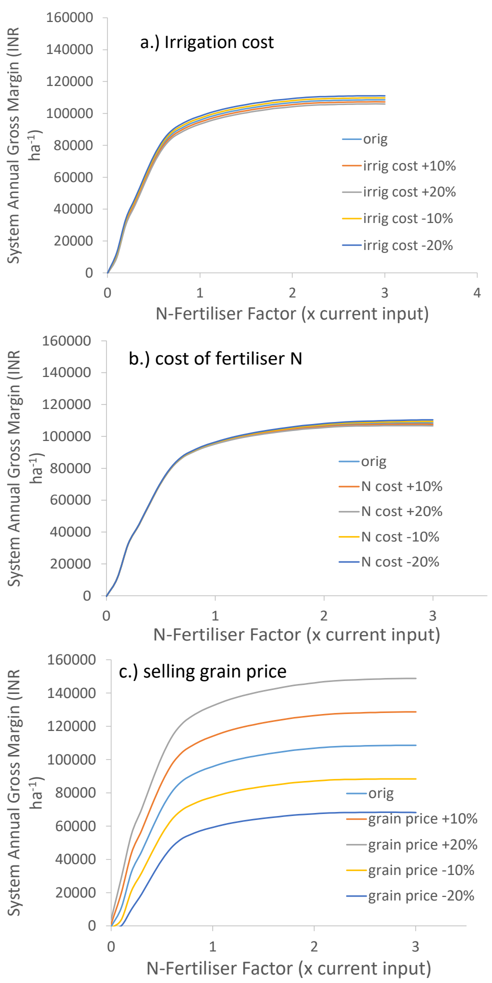

Figure 43. Sensitivity of APSIM-simulated GMs for the CT rice-wheat system (GM – in Indian Rupees, INR) in Malda, West Bengal (1995-2017), to +/- 10% and +/- 20% changes in (a) cost of irrigation; (b) cost of N fertiliser; and (c) selling price of grain.

3.2.8 Coochbehar, West Bengal, India

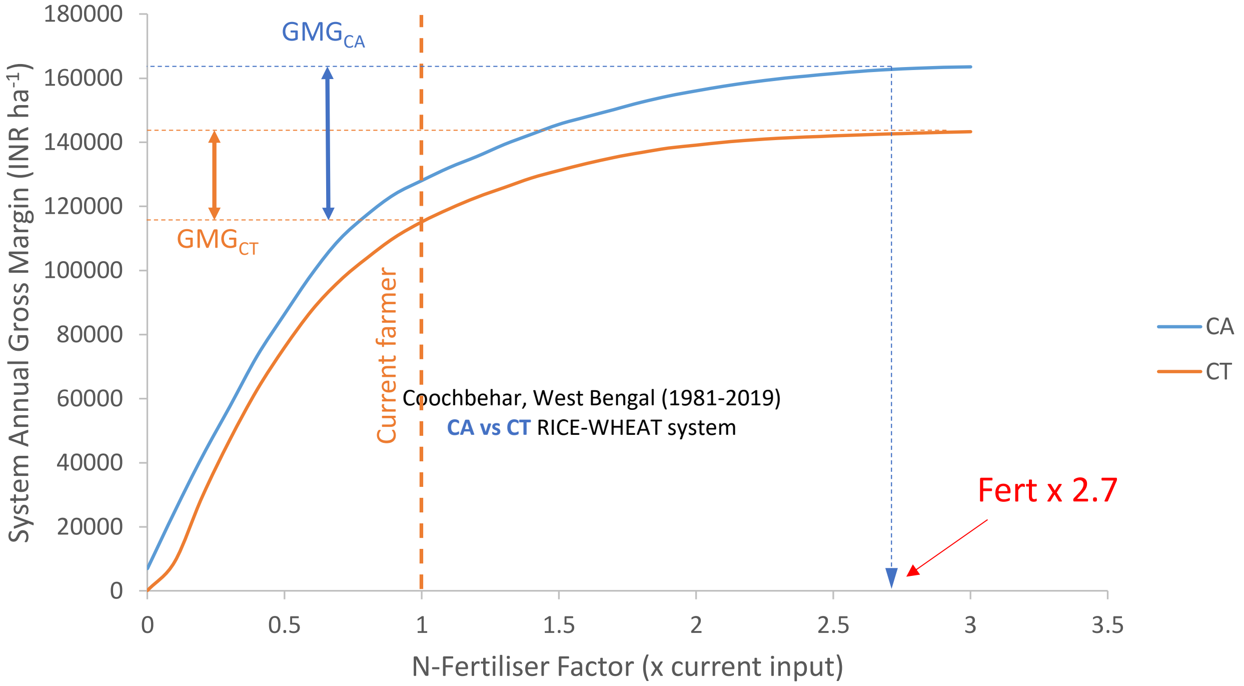

Figure 44. APSIM-simulated Gross Margins (GM – in Indian Rupees, INR) of the rice-wheat system in Coochbehar, West Bengal (1981-2019), showing the variation of optimal N-rate and possible farmer returns (gross margins) with changes in management practice (CA vs CT). The GMG_{CT} is the gross margin gap between current farmer and the optimal CT fertiliser and irrigation practice, whereas the GMG_{CA} is the gross margin gap between current farmer CT practice, and the optimal CA practice. The fertiliser multiplication factor required to reach each of these is indicated in RED

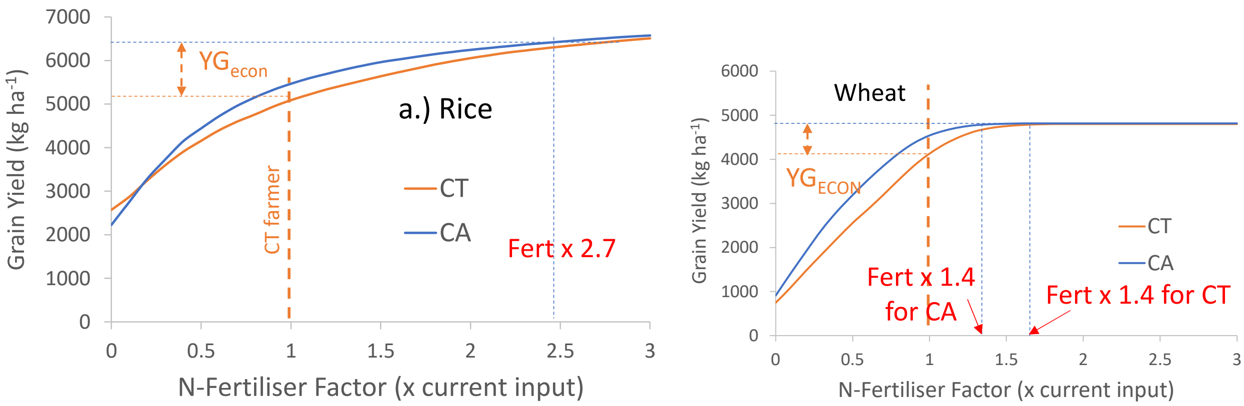

Figure 45. APSIM-simulated yields for a.) rice and b.) wheat (kg ha^{-1}) in Coochbehar, West Bengal (1981-2019), showing the yields achieved using the optimal fertiliser rates for both CT and CA practice (from Figure 44), and the resultant crop economic yield gaps.

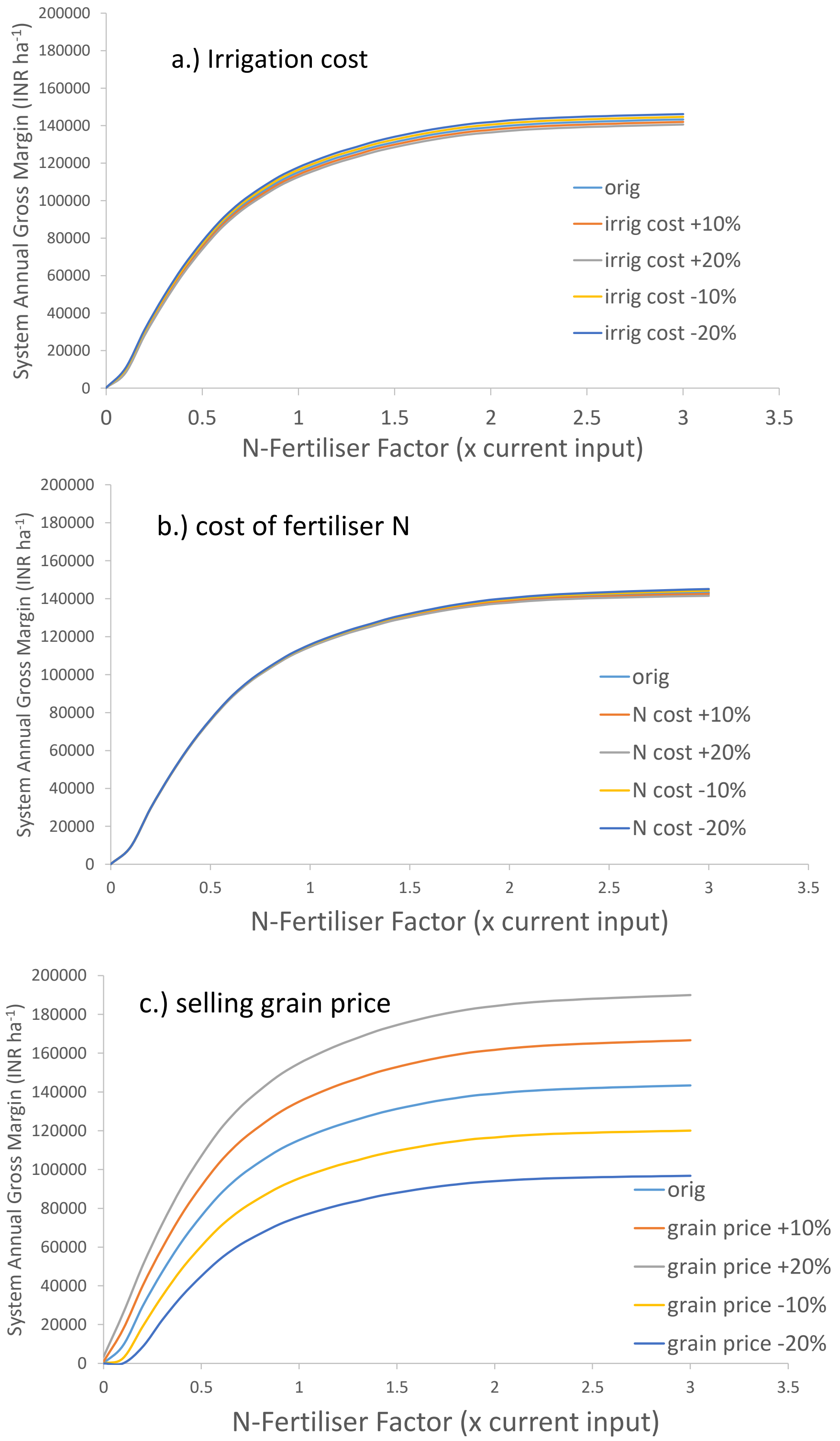

Figure 46. Sensitivity of APSIM-simulated GMs for the CT rice-wheat system (GM - Indian Rupees, INR) in **Coochbehar, West Bengal (1981-2019)**, to +/- 10% and +/- 20% changes in (a) cost of irrigation; (b) cost of N fertiliser; and (c) selling price of grain.

3.2.9 Dinajpur, Bangladesh

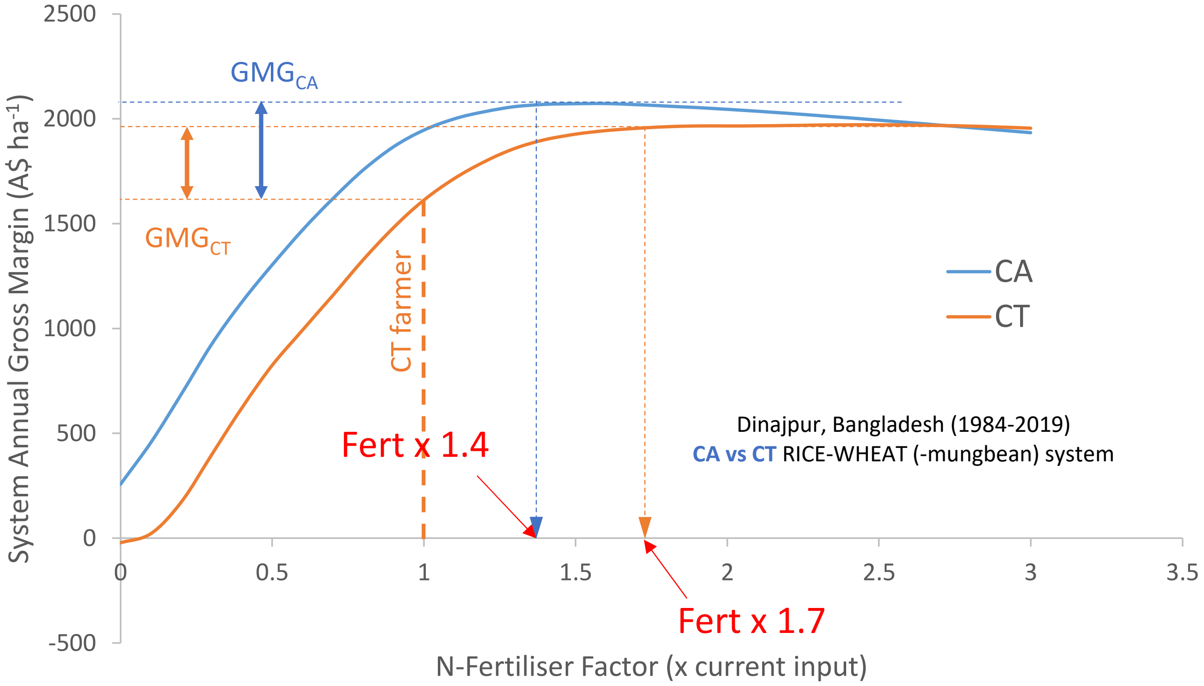

Figure 47. APSIM-simulated Gross Margins (GM – in Australian Dollars) of the rice-wheat system in **Dinajpur, Bangladesh (1984-2019)**, showing the variation of optimal N-rate and possible farmer returns (gross margins) with changes in management practice (CA vs CT). The GMG_{CT} is the gross margin gap between current farmer and the optimal CT fertiliser and irrigation practice, whereas the GMG_{CA} is the gross margin gap between current farmer CT practice, and the optimal CA practice. The fertiliser multiplication factor required to reach each of these is indicated in RED

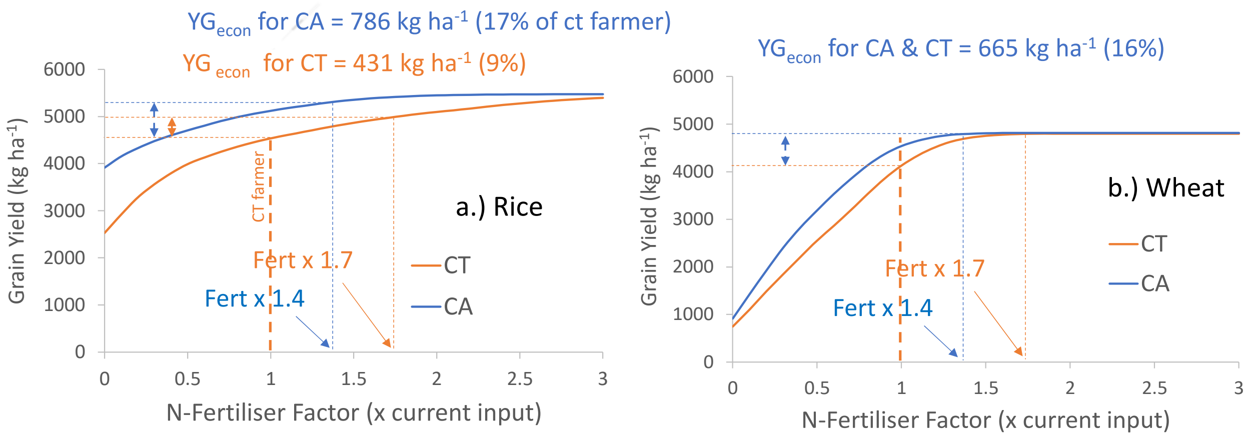

Figure 48. APSIM-simulated yields for rice and wheat (kg ha^{-1}) in **Dinajpur, Bangladesh (1984-2019)**, showing the yields achieved using the optimal fertiliser rates for both CT and CA practice (from Figure 47), and the resultant crop economic yield gaps.

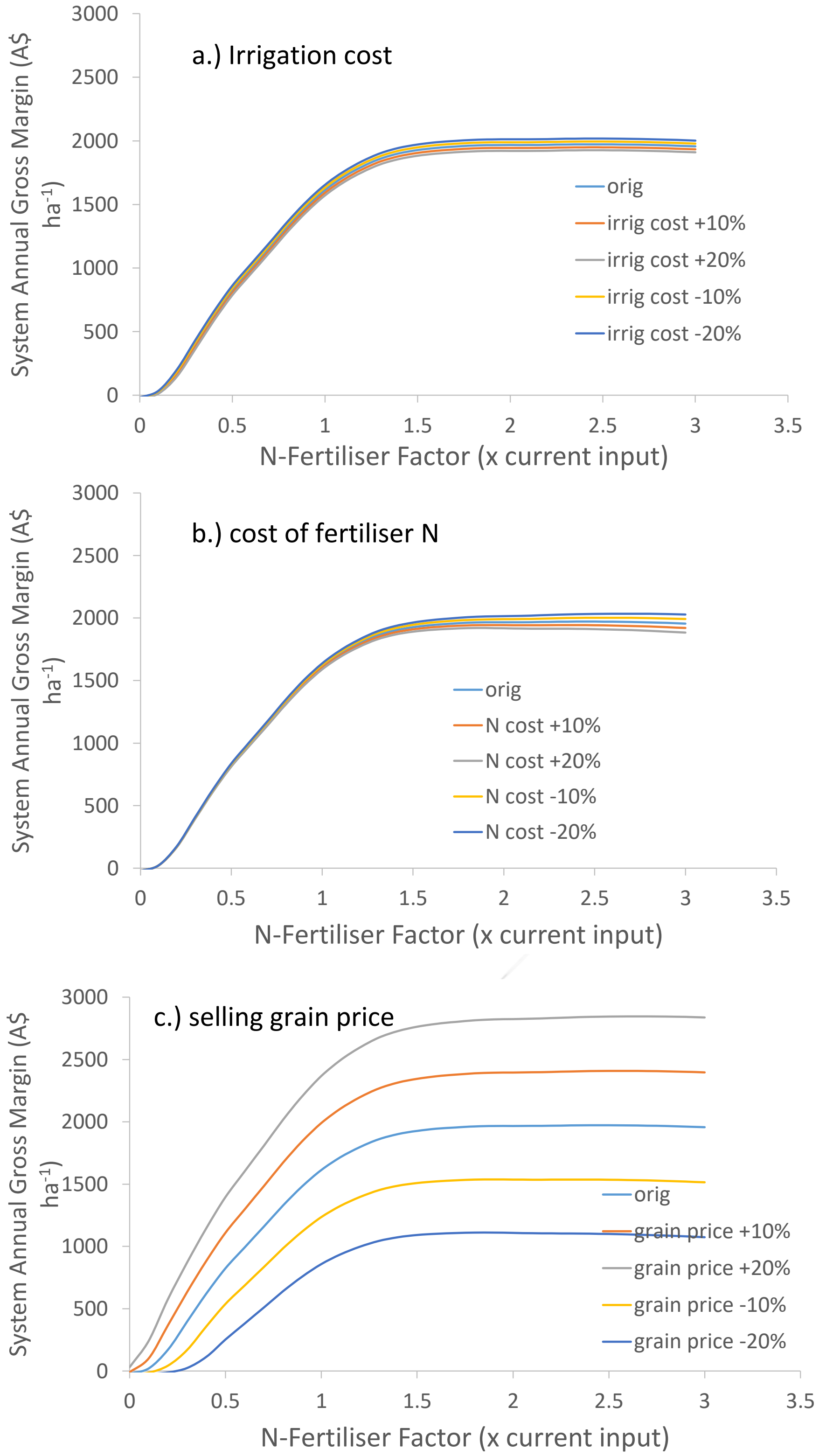

Figure 49. Sensitivity of APSIM-simulated GMs for the CT rice-wheat system (GM – in Australian Dollars) in Dinajpur, Bangladesh (1984-2019), to +/- 10% and +/- 20% changes in (a) cost of irrigation; (b) cost of N fertiliser; and (c) selling price of grain.

3.2.10 Rajshahi, Bangladesh

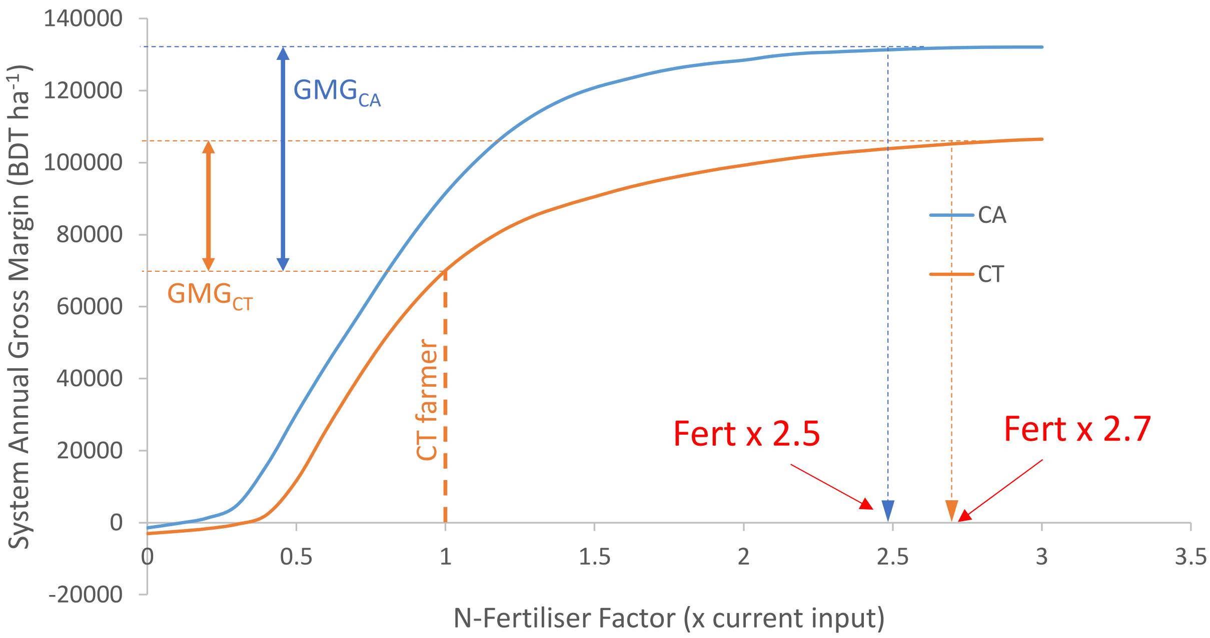

Figure 50. APSIM-simulated Gross Margins (GM – in Bangladeshi Taka, BDT) of the rice-wheat system in **Rajshahi, Bangladesh (1983-2017)**, showing the variation of optimal N-rate and possible farmer returns (gross margins) with changes in management practice (CA vs CT). The GMG_{CT} is the gross margin gap between current farmer and the optimal CT fertiliser and irrigation practice, whereas the GMG_{CA} is the gross margin gap between current farmer CT practice, and the optimal CA practice. The fertiliser multiplication factor required to reach each of these is indicated in RED

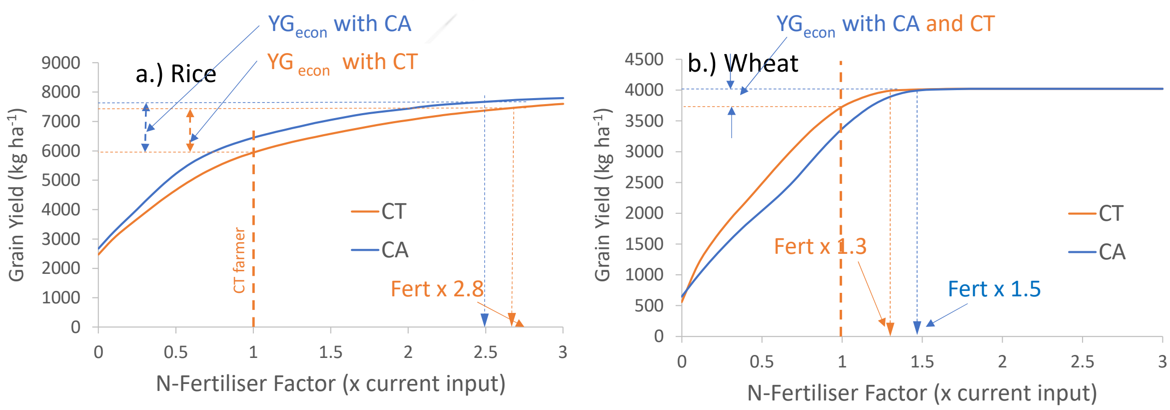

Figure 51. APSIM-simulated yields for rice and wheat (kg ha^{-1}) in **Rajshahi, Bangladesh (1983-2017)**, showing the yields achieved using the optimal fertiliser rates for both CT and CA practice (from Figure 50), and the resultant crop economic yield gaps.

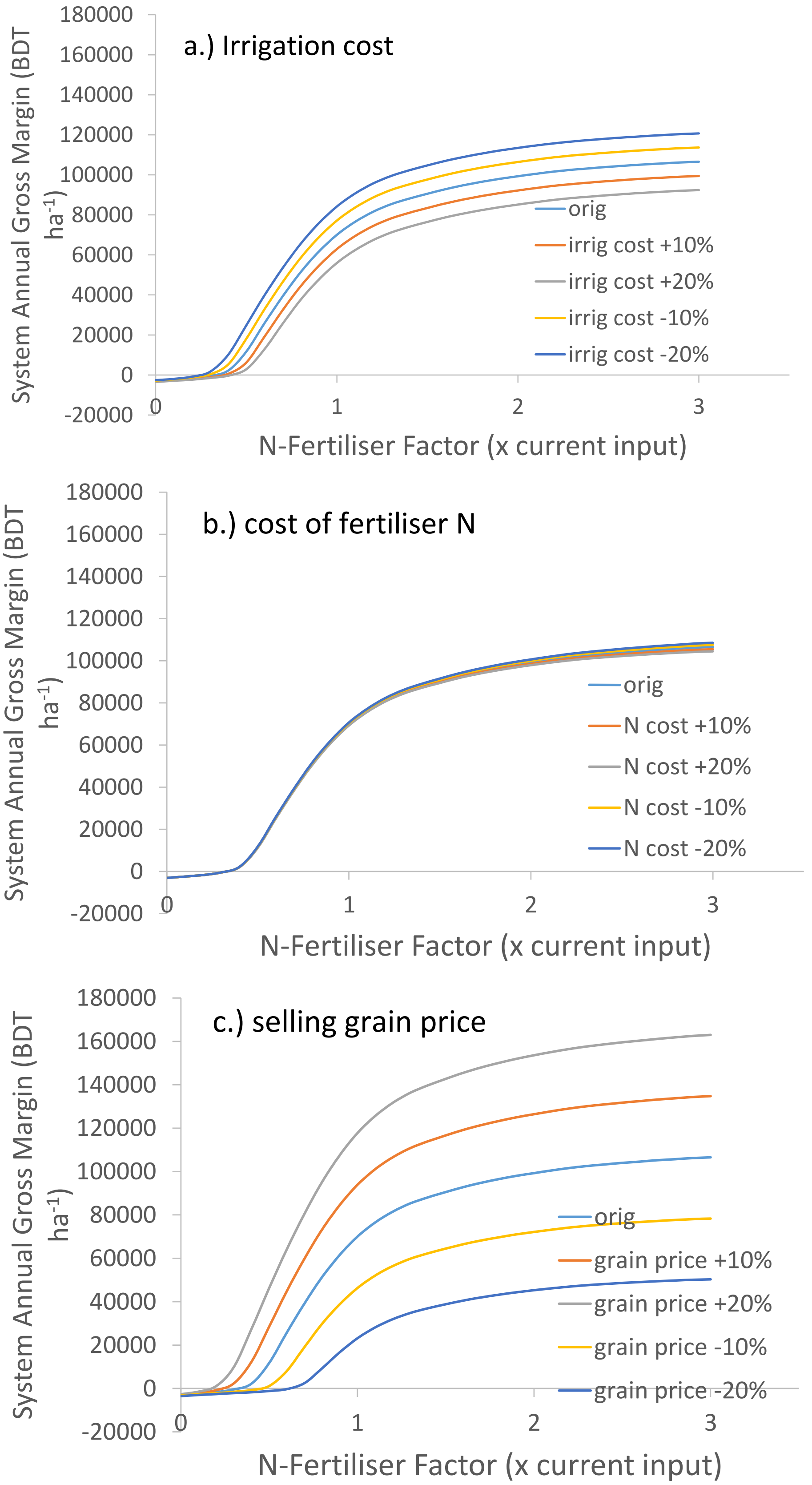

Figure 52. Sensitivity of APSIM-simulated GMs for the CT rice-wheat system (GM – in Australian Dollars) in Rajshahi, Bangladesh (1983-2017), to +/- 10% and +/- 20% changes in (a) cost of irrigation; (b) cost of N fertiliser; and (c) price of grain.

3.3 Water-sustainable Yield Gaps

3.3.1 Summary across IGP sites

Our analysis defined a water-sustainable cropping system as one in which the rainfall exceeds the water losses. This was evaluated across all sites (Figure 53) using the APSIM model and plotted in cumulative terms across several decades (varied between sites depending on availability of climate data, see earlier graphs), to allow a comparison of how 'water-sustainability' varies as we move from West to East across the IGP. The Y-Axis of each graph in Figure 53 depicts this metric of water sustainability, here referred to as "Cumulative NET Water", which is equal to the accumulated rainfall minus the cumulated ET (both in mm) across several decades.

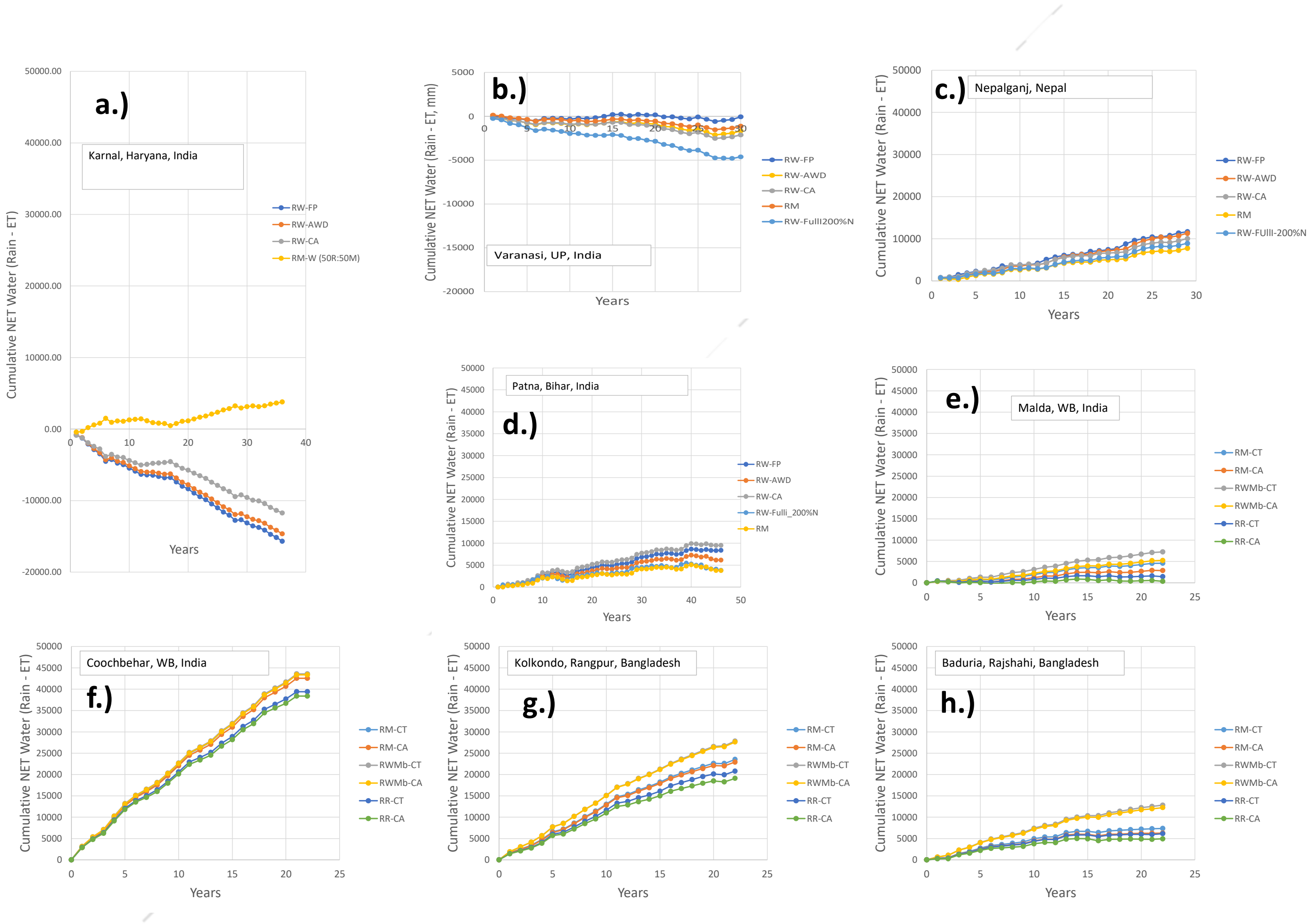

Figure 53: Summary of *water sustainability* of key farming practices across the IGP sites chosen for this research analysis, simulated using APSIM. Y-Axis is cumulative Net Water (rainfall – ET), plotted against Time (years) on the X-Axis. Sites depicted are (a) Karnal, Haryana, India; (b) Varanasi, UP, India; (c) Nepalganj, Nepal; (d) Patna, Bihar, India; (e) Malda, WB, India; (f) Coochbehar, WB, India; (g) Kolkondo, Rangpur, Bangladesh; and ((h) Baduria, Rajshahi, Bangladesh. Curves shown on each graph include

The steeper the negative slope of this curve, the greater the over-exploitation of available water. The steeper the positive slope of this curve, the greater the under-exploitation of the available water resource. The furthest Western sites (Karnal and Varanasi) are overexploited for the majority of cropping systems considered. For Karnal, the current farmer practices significantly overexploit the resource (Figure XXC (a)) and only the implementation of radically-changed cropping practices can bring the system back into sustainability (further details in the site sections below). In Varanasi, UP, the current farmer rice-wheat practices are barely sustainable. Any attempts to intensify this R-W system in Varanasi appear to result in declining water-sustainability according our analysis (Figure XXC (b)). For all other sites we considered, cropping systems currently in use are under-exploiting the water resource, some drastically (for example Coochbehar and Rangpur, Figure 53 f and g). Also, worth noting is that even implementation of widespread rice-rice rotations (in other words, largely rainfed Kharif rice followed by largely irrigated Boro rice) in many of the EGP sites seems to be 'water-sustainable' by our definition. Malda is marginal from this perspective.

Below, the results for each site is provided in greater detail, along with some considerations of how cropping systems practice might be modified to successfully increase 'water-sustainability' for the Karnal site.

3.3.2 Karnal, Haryana, India

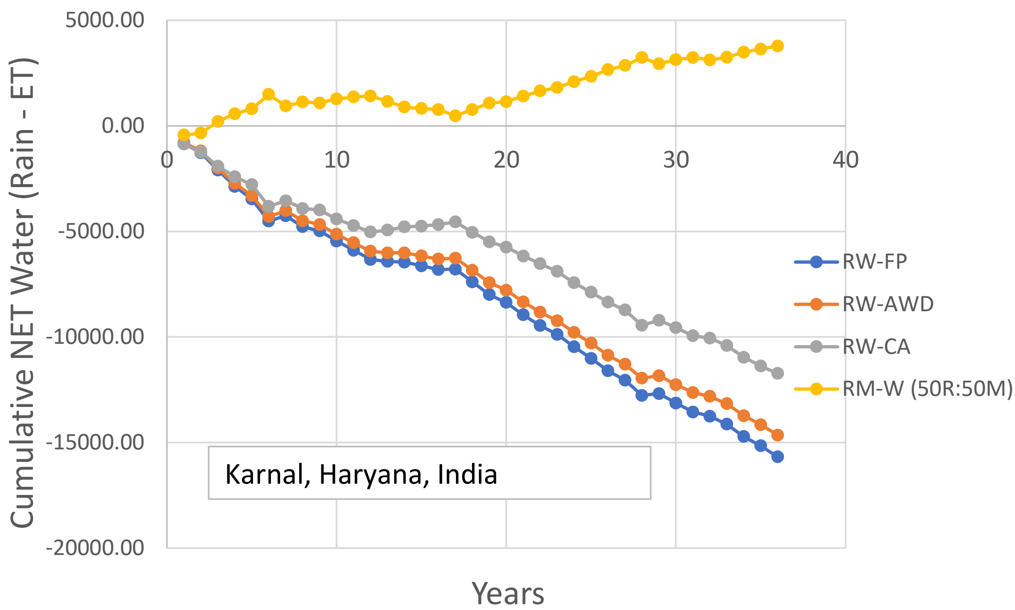

Figure 54. APSIM-simulated "Cumulative NET Water (mm)" (defined as cumulative rainfall minus cumulative ET) for the rice-wheat system in Karnal, Haryana, India (1984-2018), showing (i) rice-wheat typical farmer practice (RW-FP) ; (ii) rice-wheat typical farmer practice + AWD in rice phase (RW-AWD); (iii) rice-wheat following CA principles; and (iv) 50%rice-50%maize followed by 100% wheat.

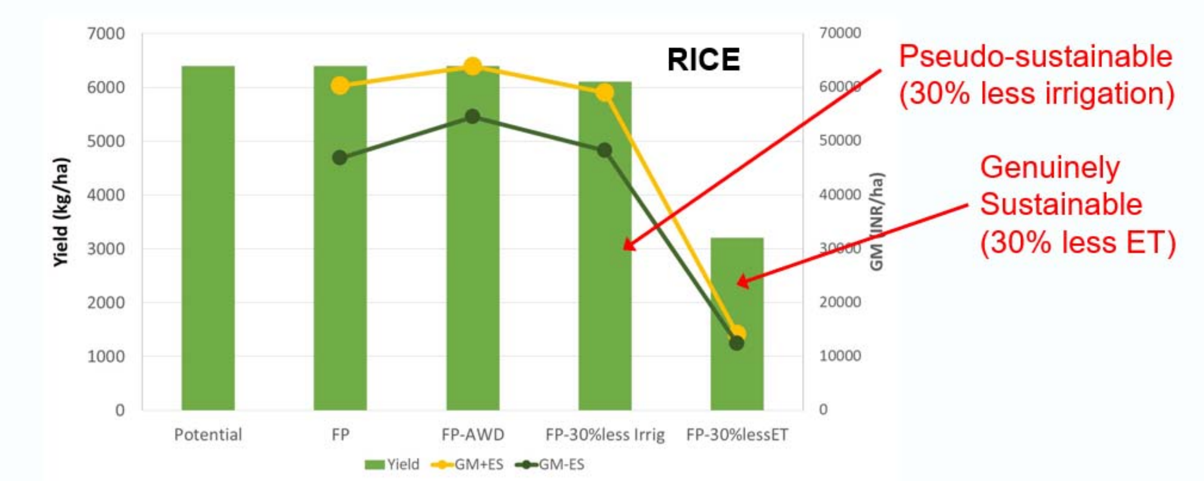

Figure 55. The effect of different farming system modifications in the Haryana rice-wheat cropping system on rice yield and GM. Note, Haryana's GW resources are currently 30% over-exploited. *FP*- farmer practice; *FP-AWD* – farmer practice with AWD irrigation practice; *FP-30%less Irrig* – current management but reducing the irrigation inputs to rice by 30%; *FP-30%less ET* – current management but reducing the irrigation inputs so that ET is reduced by 30%.

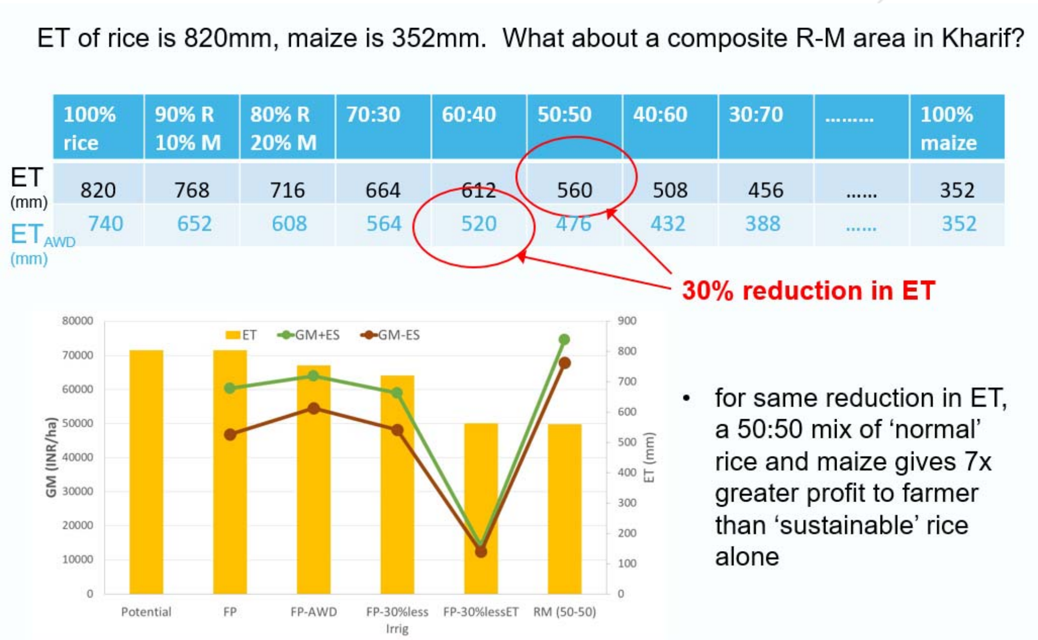

Figure 56. The effect of different farming system modifications in the Haryana rice-wheat cropping system on GM and system ET. The top section of this figure explains how different ratios in rice:maize cropped area during the Kharif season effects regional ET during that season. The current system of 100% rice has an ET of 820mm. This is 30% overexploited. System sustainability requires a seasonal ET of around 570mm, or less.

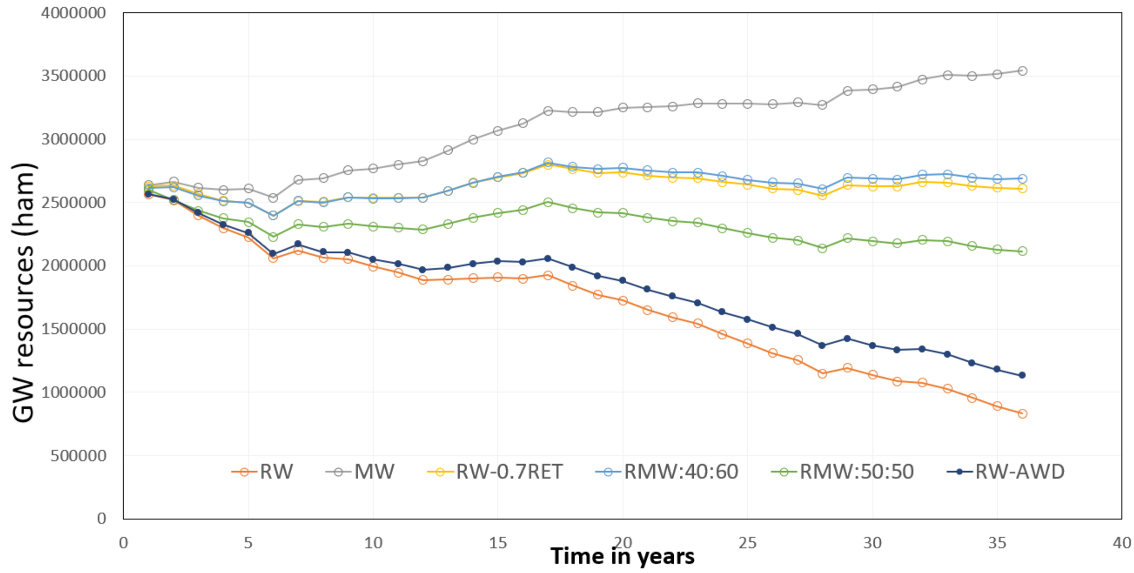

Figure 57. Change in Karnal district total ground water resources in long term (36 years) following different cropping system options. *RW* – current rice-wheat system; *MW* – theoretical change to maize-wheat; *RW-0.7RET* – rice-wheat system with a 70% of current R-W system ET (ie 30% reduced ET); *RMW:40:60* – rice and maize during kharif at 40:60 land area ratio, followed by normal wheat area (100%); *RMW:50:50* – as previous, but 50:50 for rice and maize area; *RW-AWD* – current rice-wheat practice over 100% area, but with AWD implemented in rice.

3.3.3 Varanasi, UP, India

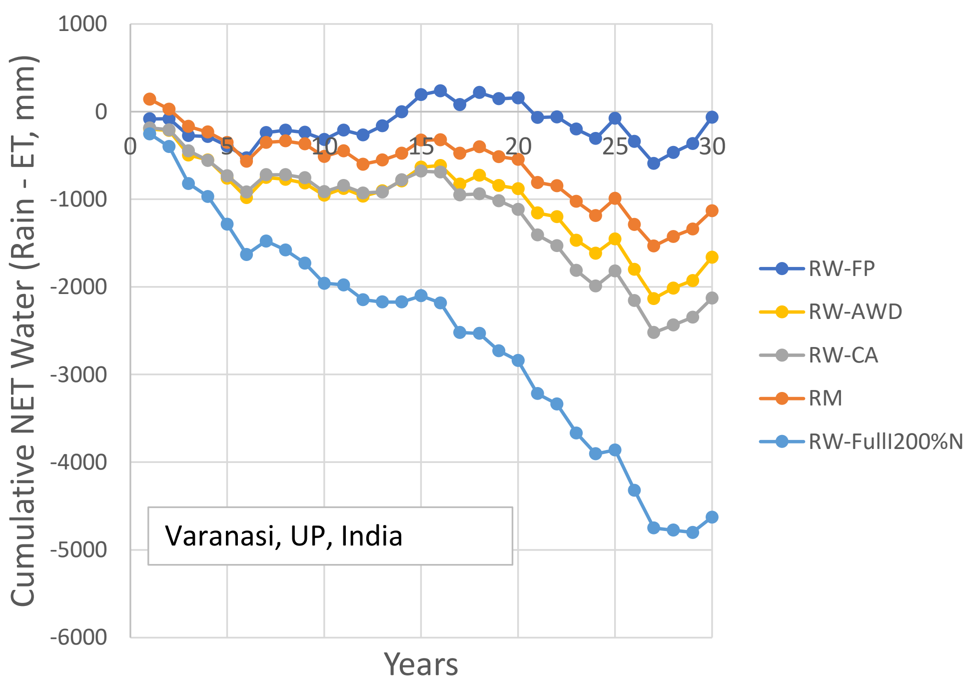

Figure 58. APSIM-simulated "Cumulative NET Water (mm)" (defined as cumulative rainfall minus cumulative ET) for the rice-wheat system in Karnal, Haryana, India (1984-2018), showing (i) rice-wheat typical farmer practice (RW-FP) ; (ii) rice-wheat typical farmer practice + AWD in rice phase (RW-AWD); (iii) rice-wheat following CA principles; and (iv) 50%rice-50%maize followed by 100% wheat.

3.3.4 Nepalganj, Western Terrai, Nepal

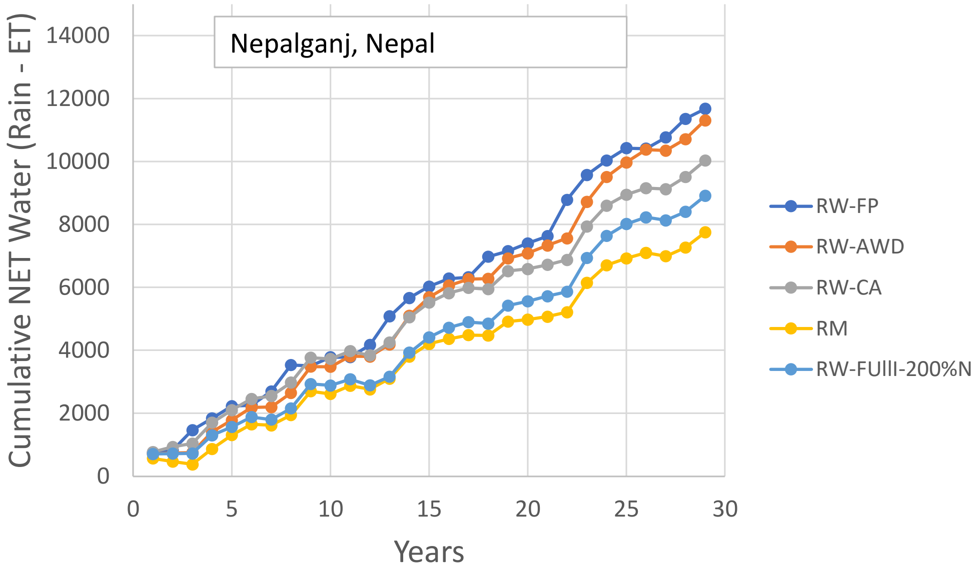

Figure 59. APSIM-simulated “Cumulative NET Water (mm)” (defined as cumulative rainfall minus cumulative ET) for the rice-wheat system in Nepalganj, Nepal (1984-2018), showing (i) rice-wheat typical farmer practice (RW-FP) ; (ii) rice-wheat typical farmer practice + AWD in rice phase (RW-AWD); (iii) rice-wheat following CA principles; and (iv) 50%rice-50%maize followed by 100% wheat.

3.3.5 Tarahara, Sunsari, Nepal

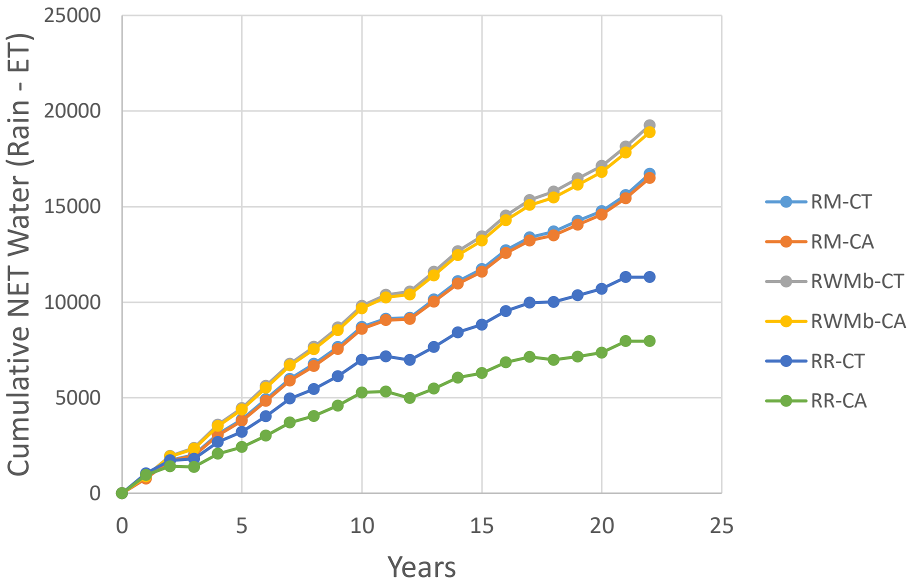

Figure 60. APSIM-simulated “Cumulative NET Water (mm)” (defined as cumulative rainfall minus cumulative ET) for the rice-wheat system in Tarahara, Sunsari, nepal (1984-2018), showing (i) rice-wheat typical farmer practice (RW-FP) ; (ii) rice-wheat typical farmer practice + AWD in rice phase (RW-AWD); (iii) rice-wheat following CA principles; and (iv) 50%rice-50%maize followed by 100% wheat.

3.3.6 Patna, Bihar, India

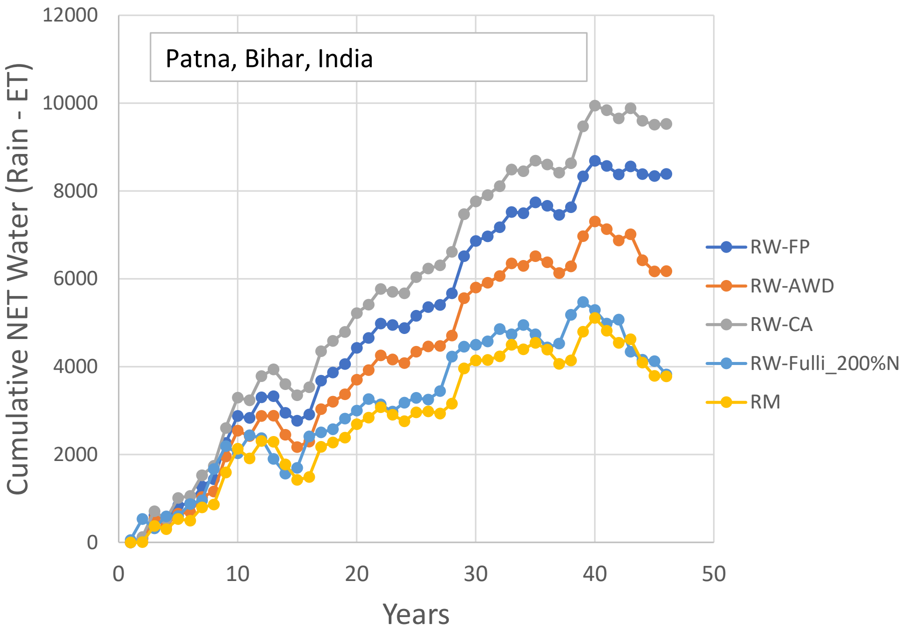

Figure 61. APSIM-simulated "Cumulative NET Water (mm)" (defined as cumulative rainfall minus cumulative ET) for the rice-wheat system in Patna, Bihar, India (1984-2018), showing (i) rice-wheat typical farmer practice (RW-FP) ; (ii) rice-wheat typical farmer practice + AWD in rice phase (RW-AWD); (iii) rice-wheat following CA principles; and (iv) 50%rice-50%maize followed by 100% wheat.

3.3.7 Malda, West Bengal, India

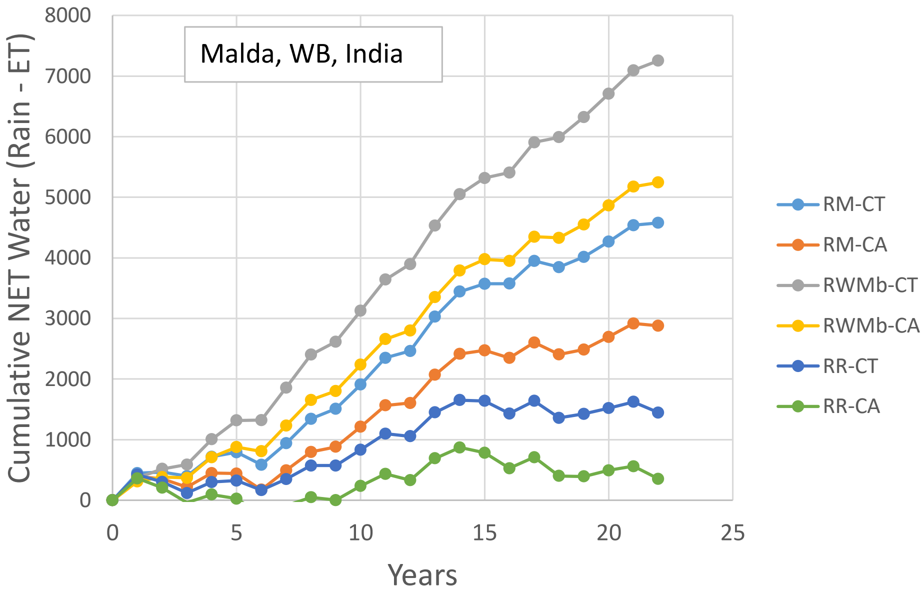

Figure 62. APSIM-simulated "Cumulative NET Water (mm)" (defined as cumulative rainfall minus cumulative ET) for the rice-wheat system in Malda, WB, India (1984-2018), showing (i) rice-wheat typical farmer practice (RW-FP) ; (ii) rice-wheat typical farmer practice + AWD in rice phase (RW-AWD); (iii) rice-wheat following CA principles; and (iv) 50%rice-50%maize followed by 100% wheat.

3.3.8 Coochbehar, West Bengal, India

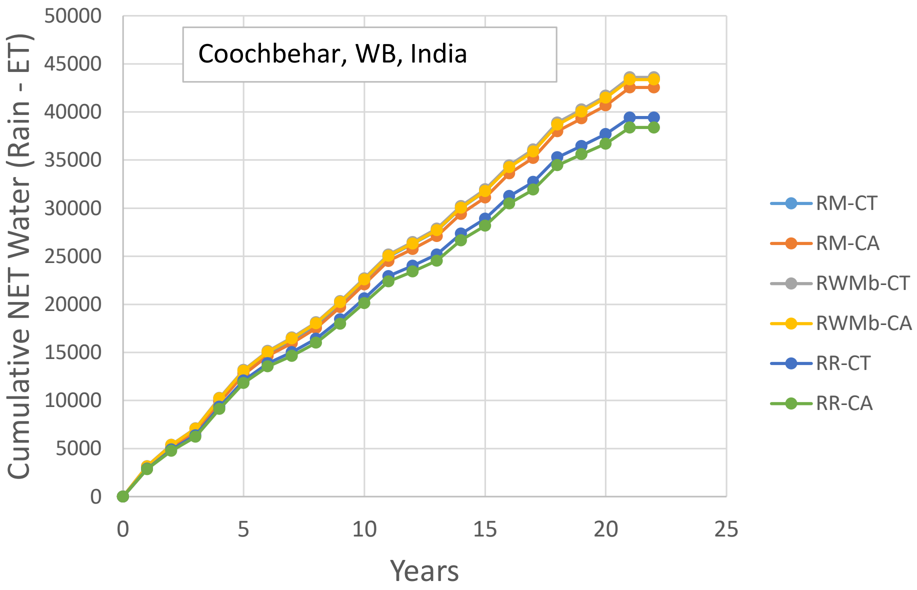

Figure 63. APSIM-simulated "Cumulative NET Water (mm)" (defined as cumulative rainfall minus cumulative ET) for the rice-wheat system in **Coochbehar, WB, India** (1984-2018), showing (i) rice-wheat typical farmer practice (RW-FP) ; (ii) rice-wheat typical farmer practice + AWD in rice phase (RW-AWD); (iii) rice-wheat following CA principles; and (iv) 50%rice-50%maize followed by 100% wheat.

3.3.9 Rangpur, Bangladesh

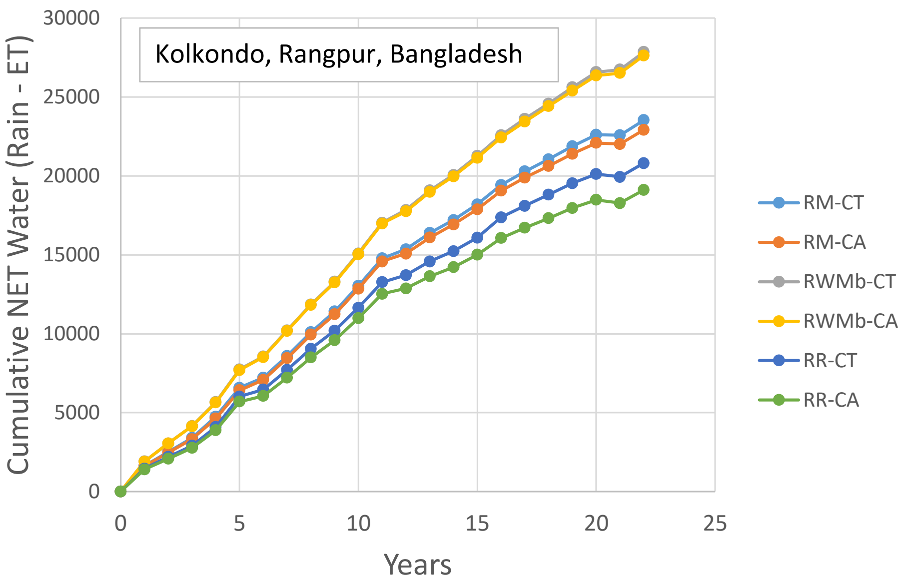

Figure 64. APSIM-simulated "Cumulative NET Water (mm)" (defined as cumulative rainfall minus cumulative ET) for the rice-wheat system in **Rangpur, Bangladesh** (1984-2018), showing (i) rice-wheat typical farmer practice (RW-FP) ; (ii) rice-wheat typical farmer practice + AWD in rice phase (RW-AWD); (iii) rice-wheat following CA principles; and (iv) 50%rice-50%maize followed by 100% wheat.

3.3.10 Rajshahi, Bangladesh

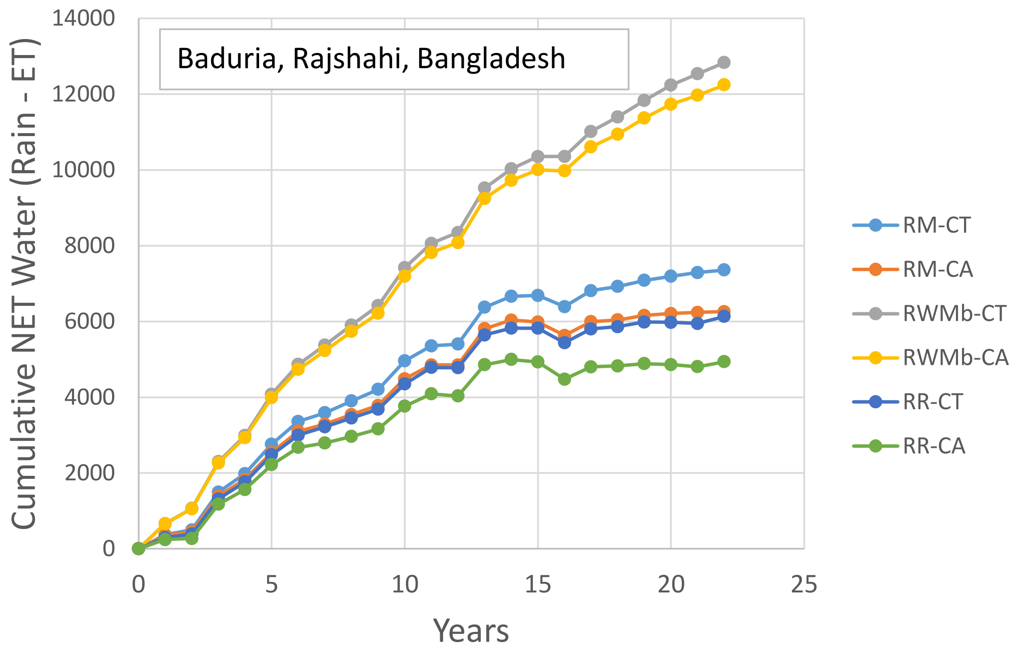

Figure 65. APSIM-simulated "Cumulative NET Water (mm)" (defined as cumulative rainfall minus cumulative ET) for the rice-wheat system in **Baduria, Rajshahi, Bangladesh** (1984-2018), showing (i) rice-wheat typical farmer practice (RW-FP) ; (ii) rice-wheat typical farmer practice + AWD in rice phase (RW-AWD); (iii) rice-wheat following CA principles; and (iv) 50%rice-50%maize followed by 100% wheat.

4 Discussion

The research conducted as part of this SRA must be viewed as a relatively superficial study based on 9 sentinel sites as representatives of the crop yield gap and water sustainability story across a geographically large and complex environment (the IGP). In this sense, our study can only point at problem issues and solutions, rather than speak authoritatively about the problems and comprehensive practical solutions for the whole IGP. We have identified water-resource sustainability across the IGP as a major issue with significant imbalances currently evident. For the future prosperity of humanity in that part of the world, effort should be made to rectify those imbalances and bring food production into line with available water resources on a region-by-region basis. In general terms the ground water resources of the far Western IGP are overexploited, whilst those of the EGP are under-exploited. But there appears to be little consideration of the whole IGP as an integrated food production system and of the need for sustainability though balance – instead each region appears focussed on itself with little consideration of what role that region should play in the whole. For example, according to our analysis the small far-West IGP states of Punjab and Haryana (currently known as the food-bowl of India – represented in our study by the sentinel site of Karnal, Haryana) need to reduce their rice production significantly to become water-sustainable in the long term. Our analysis has indicated that a reduction in rice production of up to 50-60% from these regions may be needed, and its replacement with less water-intensive crops. Our analysis has also indicated that much of the EGP has the water-resources to substantially increase rice production to counteract such a rice-deficit from the far-West IGP. It therefore seems that the EGP may be capable of significantly increasing rice production, with our RAIN-ET analysis indicating that even irrigated rice-rice rotations are sustainable in the long-term. But this clearly requires more detailed analysis, considering local idiosyncrasies related to environment, economic, social and political constraints. Our analysis of water-sustainability presented here is based on bio-physical realities of crop production and water use only.

Also, crop production by farmers in the far Western IGP is highly optimised and fine-tuned in terms of both economic and physiological yield gaps, whereas production through much of the central (MGP) and Eastern IGP is much less optimised with large physiological and economic yield gaps for major crops. The far Western IGP is also highly mechanised, whereas much of the remaining IGP (and particularly the EGP) is poised for future mechanisation. Clearly again, the future spread of mechanisation and bridging of existing crop yield gaps is a complex issue with constraining social and political aspects. The analysis we have presented here is a biophysical and basic economic analysis only and calls for further detailed examination.

4.1 Physiological Yield Gaps for major crops across the ICP

Bridging physiological yield gaps and thereby increasing food production across the IGP is an important aspiration of the region, however annual yield growth rates in rice and wheat were two to three times higher during 1966-94 than during 1995-2005 (Jat et al., 2011). The challenges of meeting future food production needs from the region are further exacerbated with ongoing rises in cost of food and energy, declining water resources in key production areas, vulnerability of soil to degradation, amongst other things (Jat et al., 2011). The key issues vary across the broad expanse of the IGP, as does the current production situation. Farmers in the far Western Gangetic Plains (WGP, for example, Haryana) operate closer to the physiological potential yield for major crops, whereas farmers of the Eastern Gangetic Plains (EGP) and much of the mid-IGP (MGP), have greater physiological yield gaps and greater potential to increase their current crop yields, according to our analysis. The reasons for this no doubt extend beyond environment and farmer knowledge, to population density and water-resource availability in addition to other non-technical aspects (Cheesman et al., 2017; Fischer 2015).

We found that the average physiological yield gap in the MGP sites (Varanasi, Nepalganj, Sunsari, Patna) is around 30% of potential yield for rice, and similar for wheat. For the EGP sites (Coochbehar, Dinajpur, Malda, Rajshahi), the figure is around 20% for rice, 25% for wheat, and 20% for maize. By contrast, in the far WGP (Karnal in our analysis) the yield gap for rice is around 2-3%, and 8% for wheat. We did not conduct a detailed investigation as to why the yield gaps existed at each site, or into which bio-physical factor was most constraining farmer production, however inputs of fertiliser (primarily N) is the likely major cause (Khaliq et al., 2019), followed by the associated need for more irrigation water for larger crops.

Others have attempted to quantify yield gaps for IGP crops, with estimates for India between 15.5-60% for irrigated crops (estimated back in 2000; Siddiq et al., 2000) and 60% for Bangladesh (Mondal et al., 2011) to more recent estimates of %%% (Smith et al., 2016). Our estimates for yield gaps are less than these, largely because our SRFSI field trial farmers (and associated CIMMYT farmers in non-SRFSI regions) achieved higher than national averages. For example, the Global Yield Gap atlas (http://www.yieldgap.org) indicates a national average irrigated wheat yield for Bangladesh of 1.6-2.4 tonnes per hectare. Practically all SRFSI farmers achieved above 3 tonnes per hectare. Farmers are often unaware of the magnitude of such yield gaps, hence often do not envisage substantially increasing yields (Mondal et al., 2011). A broader understanding of existing physiological yield gaps can only have a positive value.

The Global Yield Gap Atlas suggests that on average, these physiological yield gaps for irrigated wheat in India are 3.2-4 tonnes ha^{-1}, 4-5 tonnes ha^{-1} for irrigated rice, and 2-3 tonnes ha^{-1} for rainfed rice. Our simulated physiological yield gaps were less, generally ranging between 2-3 tonnes ha^{-1}.

At SRFSI sites, our simulated farmer yields were generally higher than farmer yields, due in part to biotic aspects which APSIM does not simulate (pests, diseases, other losses). Of particular note, the Dinajpur yield gaps were smaller than average, as the current yield figures were based on PhD experiments of Apurbo Chaki which were conducted on the Bangladesh Maize and Wheat Research Institute station. On average, the implementation of *conservation agriculture* (CA) practices reduces physiological yield gaps by around 5% (in comparison with *conventional tillage* (CT)) for crops across the IGP.

4.2 Economic Yield Gaps

The concept of an ‘economic yield gap’ recognises that it is often not economic for farmers to chase the maximum possible yields, due to high levels of inputs required and the decreasing return on investment past a certain input level. Also relevant is a farmer’s attitude to and capacity to absorb the risk of financial losses, when a crop has received high-level inputs and some unexpected calamity arises (natural disaster, pests, diseases etc.). In our analysis, we aimed to establish a realistic assessment of farmer costs and commodity prices and then use the APSIM model response to increasing input levels of fertiliser nitrogen to provide insights into the point at which further inputs became uneconomic. It’s important to note that APSIM automatically increases irrigation inputs as the crop grows larger under increasing N application, and this was explicitly taken into account in our economic calculations.

The yield gap percentage figures are difficult to compare between physiological yield gaps and our economic yield gaps, as the former are calculated based on potential yield, whereas the latter are calculated on farmer yield. This is the general protocol followed in the scientific literature and we chose to follow that. Comparison between physiological yield gaps and economic yield gaps is therefore best drawn on actual kg ha-1 figures.

We considered *Gross margin Gaps (GMG)* as a measure of cropping system performance integrated across rice and wheat, or rice and maize etc.., and as an index in which to assess the value of CA in comparison with CT. We found that simply through implementation of CA practices, GMG's of 7-31% were achieved, with SRFSI site averaging around 20%. This compares well with reported figures from the SRFSI project and literature (GM's increased by up to 25%, Gathala et al., 2021). When conventional tillage practices were left unchanged, the increase of fertiliser N and irrigation to an economic maximum achieved GMG of 13-50% illustrating that profitability of existing systems can be significantly enhanced with increasing inputs. Combined also with CA changes, this figure rises to 29-59% gross margin increases over current farmer practice.

The crop yield gaps associated with these GMG's were also determined for rice and wheat, with figures between 10-40% for rice and 18-53% for wheat above current farmer yields. These are equivalent to 500-2000 kg ha^{-1} increases in grain production. These then come in at a reduced level to physiological yield gaps (2000-3000 kg ha^{-1}), but often not by very much. In other words, under existing cost-price structures the farmer should be aiming for within 1000 kg ha^{-1} of potential yields to provide optimal economic outcomes and lessen the risks of aiming for maximum potential yield.

We also performed a sensitivity analysis into several key factors impacting farmer profit. These were (i) the cost of fertiliser N; (ii) the cost of irrigation; and (iii) the price of the final grains produced, using real input cost-price structures to which farmers are currently beholden. Across all IGP sites analysed, each with very different gross margin component costs and prices, the price that the farmer receives for their final grain produced is by far the most influential aspect in determining their profit. Cost of irrigation came next, with cost of nitrogen fertiliser the least influential of the factors we considered.

4.3 Water-sustainability and cropping across the IGP

We have engaged in significant thought and discussion with other parties to clarify what we propose are the ground-rules for genuine water-resource sustainability in cropping environments where deep drainage returns to the ground water and is hence not a real loss term (water re-enters the aquifers and is available again for irrigation). This is the situation across the whole IGP, apart from saline water table areas near the coastal zones where irrigation water draining below crop roots becomes a genuine 'loss'. For the vast majority of the IGP, the real measure of sustainable irrigation is a balance between ET (soil evaporation + crop transpiration) and GW replenishment. It is NOT correct to say that a GW overexploitation of 30% (for example) means that irrigation pumping should be decreased by 30% to bring it into sustainability. Our simulations have shown that a reduction in irrigation pumping by 30% in Haryana will decrease ET by less than 10% (Figure 55), and that to achieve a reduction in ET of 30% would result in reduced irrigation pumping of over 50%, and a rice yield reduction of around the same amount (50%), with even greater decreases in gross margin (last bar column in Figure 55).

This, we believe, will not be a practical adaptation option in over-exploited regions of the IGP. The sustainable solution will not be in reduced irrigation of existing cropping practices, but rather in replacement of water-intensive crops like rice with less-intensive crops like maize. In fact, keeping Haryana as the example, we found that substituting 50% of the regional rice area (820mm ET) with maize (352mm ET) would result in the required 30% reduction in ET (ie. GW sustainability) without any loses in farmer profit or gross margin (Figure 56). In fact, an increase in farmer profit is possible, although we realise this is a complex matter regarding markets etc.. If more extensive conservation agriculture practices in rice (like alternate wetting-and-drying (AWD)) were implemented in the region then the proportion of rice area which would need to be replace by maize falls to 40% (ie 60% rice, 40% maize in kharif season, followed by 100% of current wheat area (unchanged)). This would also be a 'water-sustainable system (Figure 56).

Another way we are visualising the "water resource sustainability" of various changed management practices is to simulate the effect on available GW water resources on a time-series basis from "net cumulative water" (daily rainfall – daily ET accumulated over a long-term sequence of years). Each cropping system will have its own specific curve in a particular environment. Any curve which does not decrease resources below a flat horizontal curve will be 'water-resource sustainable". These curves define the net water available each year by subtracting ET from rainfall. This is a simplification however is likely the best assessment we can use to judge sustainability of cropping systems water use. For example, if annual rainfall is greater than crop ET, then it is assumed that there will be no net drawdown of groundwater =resources necessary to meet crop ET demands and hence the system is "water sustainable". If, however, the annual crop ET exceeds the rain falling from above, then we assume that the excess irrigation water needed must be obtained from a net groundwater depletion.

Our analysis indicated that our far WGP site of Karnal was significantly overexploited and needs to reduce its rice production area for production to be brought back into sustainable balance with its groundwater resources. But if the current 'food-bowl' states of Punjab and Haryana (both exhibiting similar overexploitation characteristics) reduce their prodigious rice production, India still needs that rice to be produced somewhere. The obvious question is "if not there, where?". Our analysis for Varanasi, UP, indicates that any cropping system intensification above the existing farmer practice would push the water resources beyond a sustainable use level, creating another Punjab/Haryana type situation there (Figure 58). Our analysis indicates that the EGP may be in the best position to increase rice production to meet this rice shortfall. This statement is based on the substantial under-exploitation of groundwater resources indicated by our analysis at some EGP sites (Coochbehar, Rangpur; figure 53), although it is important to note that there is variability in our revealed excess "cumulative net water" and some EGP sites are marginal, particularly for rice-rice (for example, Malda; figure 53) . It therefore appears important not to view the entire EGP as being 'ready for increased exploitation'.

The SRFSI project and other initiatives have targeted 'crop diversification' as a key aspiration for the EGP. Our analysis here suggests that maybe crop diversification (substitution of rice with other non-flooded, less water intensive crops) is better suited to the currently over-exploited WGP, and that the EGP should be considered for intensification of rice production, rather than crop diversification?

5 Conclusions and recommendations

5.1 Conclusions

In this report we have used a combination of regional records, on-farm trials, on-station experiments and cropping systems modelling to examine the variation in 3 key types of crop yield gaps for major cereal crops (rice, wheat, maize) across the Indo-Gangetic Plain (IGP). Those are the *Physiological Yield Gap* (the difference in yields between what farmers currently produce and what is physiologically possible at that location), the *Economic Yield Gap* (the difference between yields that farmers currently achieve and the yields which result in maximum farmer profit at that location), and the *Water-sustainable Yield Gap* (a measure of the water-resource sustainability of current crop production at that site). We have conducted new modelling using the APSIM cropping systems model, employing data and previous model setups from the Sustainable and Resilient Farming Systems Intensification in the Eastern Gangetic Plains project ('SRFSI') (ACIAR CSE-2011-077), as well as additional CIMMYT work in the mid- and Western Gangetic Plains sites .

The key findings of this research are:

Physiological Yield Gaps

- Farmers in the far Western Gangetic Plains (WGP, for example, Haryana) operate closer to the physiological potential yield for major crops, whereas farmers of the Eastern Gangetic Plains (EGP) and much of the mid-IGP (MGP), have greater physiological yield gaps and greater potential to increase their current crop yields.
- The average physiological yield gap in the MGP sites (Varanasi, Nepalganj, Sunsari, Patna) is around 30% of potential yield for rice, and similar for wheat. For the EGP sites (Coochbehar, Dinajpur, Malda, Rajshahi), the figure is around 20% for rice, 25% for wheat, and 20% for maize. By contrast, in the far WGP (Karnal in our analysis) the yield gap for rice is around 2-3%, and 8% for wheat.
- On average, the implementation of *conservation agriculture* (CA) practices reduces physiological yield gaps by around 5% (in comparison with *conventional tillage* (CT)) for crops across the IGP.

Economic Yield Gaps

- We found that to maximise their economic returns under existing cost-price structures the farmer should be aiming for within 1000 kg ha^{-1} of potential crop yields to provide optimal economic outcomes and lessen the risks of aiming for maximum potential yield.
- Conservation agricultural practices improved gross margins by 20-30% over conventional tillage across the lesser developed parts of the IGP (MGP and ESP) with smaller gains in the far WGP.
- Implementing CA practices, together with economically optimising fertiliser N and irrigation inputs is recommended for less developed sites thought the Mid- and Eastern Gangetic plains, and our analysis indicated this could lead to gross margin gains of 29-59% over current farmer practice.

- Electricity subsidies have a significant effect on farmer profitability in the far WGP, but the effect of these subsidies decreases with less rice in the system, due to decreased GW pumping. For example, when substituting maize for rice to achieve sustainability.
- The price that farmers receive for their grain is the most influential aspect in determining their profit. Cost of irrigation came next, with cost of nitrogen fertiliser the least influential of the factors we considered.

Water-sustainable Yield Gaps

- Cropping districts in the far WGP (our example: Karnal, Haryana) currently overexploit GW resources and are farming unsustainably with their current cropping practices. This is evident from the groundwater extraction data we have assembled, and from the dynamics of groundwater depth Appendix 3). This is also supported by many reports from the literature.
- It is also evident from our analysis using an independent measure of cropping system sustainability for the IGP (cumulative Rain – APSIM-simulated cumulative ET curves, over multiple years). When these curves trend in a positive direction for a cropping system, it is considered 'water-sustainable'. When they trend in a negative direction, it predicts that a cropping system will over-exploit local water resources (see Figure ES2). Figure ES2 illustrates the water-resource impact of a range of different cropping systems at each site (different coloured curves). The measured groundwater trends which we collated (Figure ES1) correlate strongly with our APSIM simulations on water-sustainability (Figure ES2), giving some confidence in our methodology and results., but also suggesting that.
- We examined cropping system adaptation options for over exploited cropping systems in the WGP. Rice irrigation is primarily responsible for over-exploitation of groundwater resources in the region. Our analyses for Karnal (Haryana) indicate that modifying the current rice-wheat system to (40% rice:60% maize in kharif) followed by 100% wheat in Rabi is both sustainable and profitable for the region. India needs that missing 60% rice to be grown somewhere, however.
- Our analysis also suggests that many of the EGP sites examined are significantly underexploited from the perspective of water-resources. It is impossible to make a blanket statement that the EGP is 'underexploited', however our analysis indicates that some sites are highly underexploited (for example Coochbehar and Rangpur, Figure 53 *f* and *g*), whereas some are marginal (for example Malda).
- Most EGP sites are well-positioned to increase total rice production, although not just in the Kharif season. We conducted APSIM simulation of irrigated rice-rice (kharif-Rabi) systems across all EGP sites, and found that the system was water-sustainable everywhere, although some sites were standouts for water availability (Coochbehar, Rangpur. Figure 53). This, together with current yield gaps, strongly suggests the possibility of shifting key crop production (particularly rice) eastwards into the EGP in future, to relieve the pressure of rice production on water resources in the WGP.
- It also calls into question the current focus on crop diversification in the EGP, and raises the question as to whether the EGP is not better suited to carry a large load of India's rice production – with more crop diversification (less water-intensive non-rice cropping) to be encouraged in the currently over-exploited WGP?

5.2 Recommendations

We therefore recommend the following actions, in light of the findings of this SRA:

- The planning and commissioning of a comprehensive study of the IGP, focussed on evaluating scenarios for strategically balancing future crop production with available water resources across, regions, focussing on balancing the whole IGP water-food nexus/system. Such a study would need to integrate knowledge from hydrologists, agronomists, economists, spatial and GIS specialists, climate change experts, and people with insights into local and national political constraints and issues, and would aim to produce a strategic blueprint to guide regional water-resource development and agricultural production aspirations across the whole IGP. This would require a spatially integrated assessment of various future cropping system and water-resource options, instead of a point-based analysis such as this SRA presented (Lobell et al., 2013). This could be achieved by linking cropping systems modelling with GIS layers, remote sensing, and regional water-resource modelling.
- Further study into policies and strategies to encourage farmers to bridge economic yield gaps, and also the cost-benefits of governmental levers to bring economically viable crop yields closer to physiological ones.

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Appendix 1 – Site soils data

Sites of Analysis

Karnal, Haryana, India

Soil layer (cm)	Bulk density (g/cc)	Air Dry (mm/mm)	LL 15 (mm/mm)	Drained upper limit (mm/mm)	Saturation (mm/mm)	Saturated hydraulic conductivity (Ks, mm/day)	Organic C (%)	pH
0-15	1.400	0.061	0.121	0.230	0.468	40.0	1.07	7.1
15-30	1.550	0.086	0.086	0.192	0.415	2.0/4.0*	1.0	7.1
30-60	1.510	0.060	0.070	0.157	0.431	35.0	0.31	7.1
60-90	1.540	0.060	0.069	0.162	0.418	30.0	0.19	7.1
90-120	1.540	0.066	0.069	0.162	0.418	25.0	0.14	7.1
120-150	1.540	0.066	0.069	0.162	0.418	25.0	0.14	7.1

* - puddled and unpuddled Ks values

Varanasi, UP, India

Soil layer (cm)	Bulk density (g/cc)	Air Dry (mm/mm)	LL 15 (mm/mm)	Drained upper limit (mm/mm)	Saturation (mm/mm)	Saturated hydraulic conductivity (Ks, mm/day)	Organic C (%)	pH
0-15	1.400	0.061	0.121	0.230	0.468	40.0	1.07	7.1
15-30	1.550	0.086	0.086	0.192	0.415	2.0/4.0*	1.0	7.1
30-60	1.510	0.060	0.070	0.157	0.431	35.0	0.31	7.1
60-90	1.540	0.060	0.069	0.162	0.418	30.0	0.19	7.1
90-120	1.540	0.066	0.069	0.162	0.418	25.0	0.14	7.1
120-150	1.540	0.066	0.069	0.162	0.418	25.0	0.14	7.1

* - puddled and unpuddled Ks values

Nepalganj, Western Terrai, Nepal

Soil layer (cm)	Bulk density (g/cc)	Air Dry (mm/mm)	LL 15 (mm/mm)	Drained upper limit (mm/mm)	Saturation (mm/mm)	Saturated hydraulic conductivity (Ks, mm/day)	Organic C (%)	pH
0-15	1.400	0.061	0.121	0.230	0.468	40.0	1.07	7.1
15-30	1.550	0.086	0.086	0.192	0.415	2.0/4.0*	1.0	7.1
30-60	1.510	0.060	0.070	0.157	0.431	35.0	0.31	7.1
60-90	1.540	0.060	0.069	0.162	0.418	30.0	0.19	7.1
90-120	1.540	0.066	0.069	0.162	0.418	25.0	0.14	7.1
120-150	1.540	0.066	0.069	0.162	0.418	25.0	0.14	7.1

* - puddled and unpuddled Ks values

Tarahara, Sunsari, Nepal

Soil layer (cm)	Bulk density (g/cc)	Air Dry (mm/mm)	LL 15 (mm/mm)	Drained upper limit (mm/mm)	Saturation (mm/mm)	Saturated hydraulic conductivity (Ks, mm/day)	Organic C (%)	pH
0-15	1.390	0.120	0.240	0.420	0.470	60.0	0.790	5.9
15-30	1.390	0.183	0.245	0.435	0.472	40.0	0.580	5.9
30-60	1.400	0.255	0.255	0.450	0.474	2.0/4.0*	0.090	6.9
60-90	1.410	0.286	0.286	0.445	0.467	10.0	0.060	7.1
90-120	1.410	0.286	0.286	0.445	0.467	10.0	0.050	7.1
120-150	1.410	0.286	0.286	0.445	0.467	10.0	0.050	7.1

* - puddled and unpuddled Ks values

Patna, Bihar, India

Soil layer (cm)	Bulk density (g/cc)	Air Dry (mm/mm)	LL 15 (mm/mm)	Drained upper limit (mm/mm)	Saturation (mm/mm)	Saturated hydraulic conductivity (Ks, mm/day)	Organic C (%)	pH
0-15	1.400	0.061	0.121	0.230	0.468	40.0	1.07	7.1
15-30	1.550	0.086	0.086	0.192	0.415	2.0/4.0*	1.0	7.1
30-60	1.510	0.060	0.070	0.157	0.431	35.0	0.31	7.1
60-90	1.540	0.060	0.069	0.162	0.418	30.0	0.19	7.1
90-120	1.540	0.066	0.069	0.162	0.418	25.0	0.14	7.1
120-150	1.540	0.066	0.069	0.162	0.418	25.0	0.14	7.1

* - puddled and unpuddled Ks values

Malda, West Bengal, India

Soil layer (cm)	Bulk density (g/cc)	Air Dry (mm/mm)	LL 15 (mm/mm)	Drained upper limit (mm/mm)	Saturation (mm/mm)	Saturated hydraulic conductivity (Ks, mm/day)	Organic C (%)	pH
0-15	1.400	0.061	0.121	0.230	0.468	40.0	1.07	7.1
15-30	1.550	0.086	0.086	0.192	0.415	2.0/4.0*	1.0	7.1
30-60	1.510	0.060	0.070	0.157	0.431	35.0	0.31	7.1
60-90	1.540	0.060	0.069	0.162	0.418	30.0	0.19	7.1
90-120	1.540	0.066	0.069	0.162	0.418	25.0	0.14	7.1
120-150	1.540	0.066	0.069	0.162	0.418	25.0	0.14	7.1

* - puddled and unpuddled Ks values

Coochbehar, West Bengal, India

Soil layer (cm)	Bulk density (g/cc)	Air Dry (mm/mm)	LL 15 (mm/mm)	Drained upper limit (mm/mm)	Saturation (mm/mm)	Saturated hydraulic conductivity (Ks, mm/day)	Organic C (%)	pH
0-15	1.390	0.075	0.091	0.210	0.468	40.0	1.13	5.9
15-30	1.430	0.060	0.080	0.220	0.465	2.0/4.0*	1.0	5.9
30-60	1.420	0.050	0.060	0.190	0.443	35.0	0.41	5.9
60-90	1.400	0.030	0.050	0.180	0.420	30.0	0.29	5.9
90-120	1.400	0.030	0.050	0.170	0.420	25.0	0.14	5.9
120-150	1.400	0.030	0.050	0.160	0.420	25.0	0.14	5.9

* - puddled and unpuddled Ks values

Dinajpur, Bangladesh

Soil layer (cm)	Bulk density (g/cc)	Air Dry (mm/mm)	LL 15 (mm/mm)	Drained upper limit (mm/mm)	Saturation (mm/mm)	Saturated hydraulic conductivity (Ks, mm/day)	Organic C (%)	pH
0-15	1.580	0.035	0.079	0.216	0.344	13.1	0.73	4.9
15-30	1.670	0.080	0.107	0.264	0.310	10.0/20.0*	0.50	5.4
30-60	1.350	0.112	0.122	0.240	0.310	53.1	0.23	5.7
60-90	1.370	0.078	0.078	0.269	0.305	53.1	0.10	5.6
90-120	1.370	0.078	0.078	0.269	0.305	53.1	0.10	5.6
120-150	1.250	0.032	0.032	0.17	0.343	53.1	0.08	5.5

* - puddled and unpuddled Ks values

Rajshahi, Bangladesh

Soil layer (cm)	Bulk density (g/cc)	Air Dry (mm/mm)	LL 15 (mm/mm)	Drained upper limit (mm/mm)	Saturation (mm/mm)	Saturated hydraulic conductivity (Ks, mm/day)	Organic C (%)	pH
0-15	1.400	0.061	0.121	0.230	0.468	40.0	0.9	8.3
15-30	1.550	0.090	0.097	0.192	0.415	2.0/4.0*	1.0	8.3
30-60	1.510	0.060	0.070	0.157	0.431	35.0	0.31	8.3
60-90	1.540	0.060	0.069	0.162	0.418	30.0	0.19	8.3
90-120	1.540	0.066	0.069	0.162	0.418	25.0	0.14	8.3
120-150	1.540	0.066	0.069	0.162	0.418	25.0	0.14	8.3

* - puddled and unpuddled Ks values

Appendix 2 – Site gross margin data and farmer crop management

Sites of Analysis

Karnal, Haryana, India

Total area ('000ha)	246
Net sowing area ('000ha)	190
Rice area ('000ha)	171
Wheat area('000ha)	173
Ground water resources (ham)	2599195
Annual rainfall (mm)	710
Gross Margin	
Rice	
Grain Yield (INR/kg)	17.7
Input cost	
Seed cost+ treatment	817
Fertilizers	
Urea (INR/kg)	6
Phosphorus (INR/kg)	28
Potassium (INR/kg)	19
Plant Protection cost (weeds, pest and disease control)	4000
Irrigation cost (INR/m3)	0.86
Total Human labour	15190
Tractor hours cost	7960
Harvesting cost	3000
Marketing charges	1242
Wheat	
Grain Yield (INR/kg)	17.0
By product	3.25
Input cost	
Seed cost+ treatment	3302
Fertilizers	
Urea (INR/kg)	6
Phosphorus (INR/kg)	28
Potassium (INR/kg)	19
Plant Protection cost (weeds, pest and disease control)	2210

Irrigation cost (INR/m3)	0.86
Total Human labour	4725
Tractor hours cost	6750
Harvesting cost	7000
Marketing charges	602.5
variety duration	
Crop Management practices	
Rice	
Rice transplanting date	10 June
N fertilizer rate (kg/ha)	140
P rate (kg/ha)	60
K rate (kg/ha)	40
Irrigation number	22
variety duration	155
Wheat	
Sowing date	15 days after rice harvesting
N fertilizer rate (kg/ha)	140
P rate (kg/ha)	50
K rate (kg/ha)	30
Irrigation number	5
variety duration	150

Varanasi, UP, India

Total area (‘000ha)	157
Net sowing area (‘000ha)	95
Rice area (‘000ha)	42
Wheat area(‘000ha)	72
Ground water resources (ham)	47972
Annual rainfall (mm)	820
Gross Margin	
Rice	
Grain Yield (INR/kg)	15.5
Input cost	
Seed cost+ treatment	1241
Fertilizers	
Urea (INR/kg)	16
Phosphorus (INR/kg)	50
Potassium (INR/kg)	28
Plant Protection cost (weeds, pest and disease control)	2200
Irrigation cost (INR/m3)	33
Total Human labour	12136
Tractor hours cost	2834
Harvesting cost	
Marketing charges	
Wheat	
Grain Yield (INR/kg)	16
By product	3
Input cost	
Seed cost+ treatment	3450
Fertilizers	
Urea (INR/kg)	16
Phosphorus (INR/kg)	50
Potassium (INR/kg)	28
Plant Protection cost (weeds, pest and disease control)	775
Irrigation cost (INR/m3)	33
Total Human labour	13420
Tractor hours cost	7540
Harvesting cost	
Marketing charges	
Crop Management practices	
Rice	
Rice transplanting date	30 July
N fertilizer rate (kg/ha)	145
P rate (kg/ha)	45
K rate (kg/ha)	25

Irrigation number	4
variety duration	142
Wheat	
Sowing date	3 weeks after rice harvesting
N fertilizer rate (kg/ha)	153
P rate (kg/ha)	50
K rate (kg/ha)	25
Irrigation number	3
variety duration	145

Nepalganj, Western Terrai, Nepal

Total area ('000ha)	
Net sowing area ('000ha)	
Rice area ('000ha)	
Wheat area('000ha)	
Ground water resources (ham)	
Annual rainfall (mm)	1260
Gross Margin	
Rice	
Grain Yield (INR/kg)	18
Input cost	
Seed cost+ treatment	5493
Fertilizers	
Urea (INR/kg)	11.5
Phosphorus (INR/kg)	29
Potassium (INR/kg)	22
Plant Protection cost (weeds, pest and disease control)	2200
Irrigation cost (INR/m3)	60
Total Human labour	29145
Tractor hours cost	
Harvesting cost	
Marketing charges	
Wheat	
Grain Yield (INR/kg)	14.7
By product	3
Input cost	
Seed cost+ treatment	3535
Fertilizers	
Urea (INR/kg)	11.4
Phosphorus (INR/kg)	30
Potassium (INR/kg)	25
Plant Protection cost (weeds, pest and disease control)	775
Irrigation cost (INR/m3)	60
Total Human labour	9457
Tractor hours cost	4973
Harvesting cost	
Marketing charges	
Crop Management practices	
Rice	
Rice transplanting date	190
N fertilizer rate (kg/ha)	97
P rate (kg/ha)	49
K rate (kg/ha)	23

Irrigation number	3
variety duration	142
Wheat	
Sowing date	3 weeks after rice harvesting
N fertilizer rate (kg/ha)	54
P rate (kg/ha)	23
K rate (kg/ha)	14
Irrigation number	3
variety duration	145

Tarahara, Sunsari, Nepal

From Gathala et al., 2020

Input or output †	Bangladesh	Nepal	Bihar	West Bengal
Inputs				
Labor wage (AUD person-day^{-1})	4.3-5.1	3.7-5.0	3.8-4.4	4.0-5.0
Tillage cost (AUD ha^{-1}pass^{-1}) §	38-43	43-56	36-42	37-45
Machinery seeding cost (AUD ha^{-1}pass^{-1}) ¶	47-64	50-59	60-67	47-64
Maize seed (AUD kg^{-1})	6.6-7.7	5.0-6.8	5.9-6.6	5.9-6.6
Wheat seed (AUD kg^{-1})	0.60-0.68	0.74-0.81	0.68-0.89	0.55-0.59
Rice seed (AUD kg^{-1})	0.60-1.02	0.56-0.62	0.73-0.79	1.49-1.98
Lentil seed (AUD kg^{-1})	--	1.36-1.98	–	1.78-2.08
Munbean seed (AUD kg^{-1})	2.56	--	–	2.38
Jute seed (AUD kg^{-1})	3.8	--	–	3.2
NPK (AUD kg^{-1})	--	--	–	0.46
Urea (AUD kg^{-1})	0.27-0.29	0.25-0.37	0.12-0.20	0.12-0.14
DAP (AUD kg^{-1})	--	0.57-0.68	0.48-0.52	0.50-0.52
TSP (AUD kg^{-1})	0.39-0.43	--	–	--
MoP (AUD kg^{-1})	0.26-0.27	0.40-0.62	0.24-0.36	0.32-0.36
Gypsum (AUD kg^{-1})	0.17-0.20	--	–	--
$ZnSO_4$ (AUD kg^{-1}))	2.22-2.73	--	–	18.8
Borax (AUD kg^{-1})	4.3-5.0	--	–	7.9-9.5
Irrigation charge (AUD hr^{-1}) ‡	1.70-1.88	1.86-2.74	1.78-2.38	1.79-2.18
Fuel cost (diesel, AUD lt^{-1})	1.18	1.19	1.07-1.34	0.99-1.33
Shelling cost (AUD t^{-1} grain)	--	17	16-20	20-24
Herbicides cost*				
Glyphosate (AUD lt^{-1})	12.4-15.1	7.7-8.7	6.9-9.3	7.3-7.7
Atrazine (AUD lt^{-1})	25.6	6.8	6.3	6.3
Carfentrazone (AUD kg^{-1})	256	--	–	248
Metribuzeine (AUD kg^{-1})	--	--	26.2	26.2
Carbosulfan (AUD kg^{-1})	11.9	--	–	--
2,4-D (AUD kg^{-1})	--	6.7	23. 8-24.8	--
Pendimethalin (AUD kg $^{-1}$)		9.9-10.7	6.1	6.1
Bispyribac (AUD lt^{-1})	--	166-186	139-151	139-151
Pyrazosulfuron ethyl (AUD kg^{-1})	--	--	–	75
Tembotorine (AUD lt^{-1})	--	--	–	30
Outputs				
Maize grain sale price (AUD t^{-1})	290	285	258-277	238-277
Maize stover price (AUD t^{-1})	17-34	37	20-40	20-40
Wheat grain sale price (AUD t^{-1})	392-460	335-347	298-317	277-317
Wheat straw sale price (AUD t^{-1})	34	37-99	40-119	40
Rice grain sale price (AUD t^{-1})	239-341	211-310	198-297	238-277
Rice straw sale price (AUD t^{-1})	17-51	25-50	40	30-40
Lentil grain sale price (AUD t^{-1})	--	868-992	–	951-1387
Lentil straw sale price (AUD t^{-1})	85-136	37-99	99-139	99-159
Jute fibre sale price (AUD t^{-1})	682	--	–	793
Jute stick sale price (AUD t^{-1})	34	--	–	99
Mungbean grain sale price (AUD t^{-1})	1193	--	–	1189-1288
Mungbean straw sale price (AUD t^{-1})	85	--	–	50-70

†Ranges represent input and output prices/costs across growing seasons in the three countries (averages for Rajshahi and Rangpur in Bangladesh, Coochbehar and Malda in West Bengal, Madhubani and Purnea in Bihar, and Dhanusha and Sunsari in Nepal); ‡applied by shallow tube well; §applies to CT and puddled transplanted rice; AUD conversion factor INR=50.47, BDT=58.66 and NPR=80.57 (www.oanda.com) *Listed above are the ones most commonly used by farmers

Patna, Bihar, India

Total area ('000ha)	246
Net sowing area ('000ha)	196
Rice area ('000ha)	135
Wheat area('000ha)	95
Ground water resources (ham)	96455
Annual rainfall (mm)	1120
Gross Margin	
Rice	
Grain Yield (INR/kg)	15.5
Input cost	
Seed cost+ treatment	856
Fertilizers	
Urea (INR/kg)	17.3
Phosphorus (INR/kg)	51
Potassium (INR/kg)	32
Plant Protection cost (weeds, pest and disease control)	3162
Irrigation cost (INR/m3)	42
Total Human labour	15315
Tractor hours cost	2238
Harvesting cost	
Marketing charges	
Wheat	
Grain Yield (INR/kg)	15.5
By product	3
Input cost	
Seed cost+ treatment	3450
Fertilizers	
Urea (INR/kg)	17.3
Phosphorus (INR/kg)	51
Potassium (INR/kg)	32
Plant Protection cost (weeds, pest and disease control)	875
Irrigation cost (INR/m3)	42
Total Human labour	9110
Tractor hours cost	6317
Harvesting cost	
Marketing charges	
Crop Management practices	
Rice	

Rice transplanting date	20 July
N fertilizer rate (kg/ha)	140
P rate (kg/ha)	45
K rate (kg/ha)	25
Irrigation number	3
variety duration	145
Wheat	
Sowing date	3 weeks after rice harvest
N fertilizer rate (kg/ha)	140
P rate (kg/ha)	
K rate (kg/ha)	
Irrigation number	2
variety duration	150

Malda and Coochbehar, West Bengal, India

From Gathala et al., 2020

Input or output †	Bangladesh	Nepal	Bihar	West Bengal
Inputs				
Labor wage (AUD person-day^{-1})	4.3-5.1	3.7-5.0	3.8-4.4	4.0-5.0
Tillage cost (AUD ha^{-1}pass^{-1}) §	38-43	43-56	36-42	37-45
Machinery seeding cost (AUD ha^{-1}pass^{-1}) ¶	47-64	50-59	60-67	47-64
Maize seed (AUD kg^{-1})	6.6-7.7	5.0-6.8	5.9-6.6	5.9-6.6
Wheat seed (AUD kg^{-1})	0.60-0.68	0.74-0.81	0.68-0.89	0.55-0.59
Rice seed (AUD kg^{-1})	0.60-1.02	0.56-0.62	0.73-0.79	1.49-1.98
Lentil seed (AUD kg^{-1})	--	1.36-1.98	–	1.78-2.08
Munbean seed (AUD kg^{-1})	2.56	--	–	2.38
Jute seed (AUD kg^{-1})	3.8	--	–	3.2
NPK (AUD kg^{-1})	--	--	–	0.46
Urea (AUD kg^{-1})	0.27-0.29	0.25-0.37	0.12-0.20	0.12-0.14
DAP (AUD kg^{-1})	--	0.57-0.68	0.48-0.52	0.50-0.52
TSP (AUD kg^{-1})	0.39-0.43	--	–	--
MoP (AUD kg^{-1})	0.26-0.27	0.40-0.62	0.24-0.36	0.32-0.36
Gypsum (AUD kg^{-1})	0.17-0.20	--	–	--
$ZnSO_4$ (AUD kg^{-1}))	2.22-2.73	--	–	18.8
Borax (AUD kg^{-1})	4.3-5.0	--	–	7.9-9.5
Irrigation charge (AUD hr^{-1}) ‡	1.70-1.88	1.86-2.74	1.78-2.38	1.79-2.18
Fuel cost (diesel, AUD lt^{-1})	1.18	1.19	1.07-1.34	0.99-1.33
Shelling cost (AUD t^{-1} grain)	--	17	16-20	20-24
Herbicides cost*				
Glyphosate (AUD lt^{-1})	12.4-15.1	7.7-8.7	6.9-9.3	7.3-7.7
Atrazine (AUD lt^{-1})	25.6	6.8	6.3	6.3
Carfentrazone (AUD kg^{-1})	256	--	–	248
Metribuzeine (AUD kg^{-1})	--	--	26.2	26.2
Carbosulfan (AUD kg^{-1})	11.9	--	–	--
2,4-D (AUD kg^{-1})	--	6.7	23. 8-24.8	--
Pendimethalin (AUD kg $^{-1}$)		9.9-10.7	6.1	6.1
Bispyribac (AUD lt^{-1})	--	166-186	139-151	139-151
Pyrazosulfuron ethyl (AUD kg^{-1})	--	--	–	75
Tembotorine (AUD lt^{-1})	--	--	–	30
Outputs				
Maize grain sale price (AUD t^{-1})	290	285	258-277	238-277
Maize stover price (AUD t^{-1})	17-34	37	20-40	20-40
Wheat grain sale price (AUD t^{-1})	392-460	335-347	298-317	277-317
Wheat straw sale price (AUD t^{-1})	34	37-99	40-119	40
Rice grain sale price (AUD t^{-1})	239-341	211-310	198-297	238-277
Rice straw sale price (AUD t^{-1})	17-51	25-50	40	30-40
Lentil grain sale price (AUD t^{-1})	--	868-992	–	951-1387
Lentil straw sale price (AUD t^{-1})	85-136	37-99	99-139	99-159
Jute fibre sale price (AUD t^{-1})	682	--	–	793
Jute stick sale price (AUD t^{-1})	34	--	–	99
Mungbean grain sale price (AUD t^{-1})	1193	--	–	1189-1288
Mungbean straw sale price (AUD t^{-1})	85	--	–	50-70

†Ranges represent input and output prices/costs across growing seasons in the three countries (averages for Rajshahi and Rangpur in Bangladesh, Coochbehar and Malda in West Bengal, Madhubani and Purnea in Bihar, and Dhanusha and Sunsari in Nepal); ‡applied by shallow tube well; §applies to CT and puddled transplanted rice; AUD conversion factor INR=50.47, BDT=58.66 and NPR=80.57 (www.oanda.com) *Listed above are the ones most commonly used by farmers

Dinajpur, Rajshahi, and Rangpur, Bangladesh

Kharif	Conventional: PTR Rice					
Output	Yield/ha		Tk/unit		Tk/ha	Tk/Bigha
Rice	5,464	kg @	BDT 17.10	/kg	BDT 93,434	BDT 12,502
Rice straw	7,650	kg @	BDT 2.00	/kg	BDT 15,300	BDT 2,047
Total output					**BDT 108,734**	**BDT 14,548.66**
Costs	Rate/ha		Tk/unit		Tk/ha	Tk/Bg
Seed						
Rice	35	kg @	BDT 35.00	/kg	BDT 1,225	BDT 164
			-		-	-
Fertiliser						
Urea	195	kg @	BDT 16.00	/kg	BDT 3,125	BDT 418
TSP	50	kg @	BDT 22.00	/kg	BDT 1,100	BDT 147
Mop	72	kg @	BDT 14.00	/kg	BDT 1,008	BDT 135
Gypsum	56	kg @	BDT 7.50	/kg	BDT 422	BDT 56
Zinc	6	kg @	BDT 210.00	/kg	BDT 1,172	BDT 157
Herbicides						
			-		-	-
			-		-	-
			-		-	-
Pesticides						
Virtako	0.035	kg @	BDT 27,000.00	/kg	BDT 945.00	BDT 126.44
Amistar TOP	0.75	L @	BDT 3,600.00	/L	BDT 2,700.00	BDT 361.26
			-		-	-
Machine operations						
Cultivator	2	pass @	BDT 1,875.00	/pass	BDT 3,750	BDT 502
Wet tillage (puddling)	2	pass @	BDT 3,000.00	/pass	BDT 6,000	BDT 803
Threshing	5,464	kg @	BDT 1.25	/kg	BDT 6,830	BDT 914
Irrigation	25	hr @	BDT 125.00	/hr	BDT 3,125.00	BDT 418.13
			-		-	-
Labour operations						
Seedling raising, uprooting and transplanting	32	p day @	BDT 350.00	/p day	BDT 11,200	BDT 1,499
Fertilising and irrigation	6	p day @	BDT 350.00	/p day	BDT 2,100	BDT 281

Weeding	25	p day @	BDT 350.00	/p day	BDT 8,750	BDT 1,171
Spraying pesticides	4	p day @	BDT 350.00	/p day	BDT 1,400	BDT 187
Harvesting	30	p day @	BDT 350.00	/p day	BDT 10,500	BDT 1,405
Total costs					**BDT 65,351**	**BDT 8,744**
Gross margins					**BDT 43,383**	**BDT 5,805**

Rabi	**Conventional CT Wheat (3 irrig)**					
Output	**Yield/ha**		**Tk/unit**		**Tk/ha**	**Tk/Bg**
Wheat	3,143	kg @	BDT 26.79	/kg	BDT 84,201	BDT 11,266
Wheat straw	6,553	kg @	BDT -	/kg	BDT -	BDT -
Total output					**BDT 84,201**	**BDT 11,266**
Costs	**Rate/ha**		**Tk/unit**		**Tk/ha**	**Tk/Bg**
Seed						
Wheat	120	kg @	BDT 50.00	/kg	BDT 6,000	BDT 803
			-		-	-
Fertiliser						
Urea	260	kg @	BDT 16.00	/kg	BDT 4,166	BDT 557
TSP	100	kg @	BDT 22.00	/kg	BDT 2,200	BDT 294
Mop	108	kg @	BDT 14.00	/kg	BDT 1,512	BDT 202
Gypsum	69	kg @	BDT 7.50	/kg	BDT 516	BDT 69
Zinc	10	kg @	BDT 210.00	/kg	BDT 2,051	BDT 274
Boron	3	kg @	BDT 460.00	/kg	BDT 1,352	BDT 181
Herbicides						
Affinity	1.5	L @	BDT 1,930.00	/L	BDT 2,895.00	BDT 387.35
			-		-	-
Pesticides						
Nativo	0.6	kg @	BDT 6,600.00	/kg	BDT 3,960.00	BDT 529.85
			-		-	-
			-		-	-
Machine/animal operations						
Cultivator	4	pass @	BDT 1,875.00	/pass	BDT 7,500	BDT 1,004

Laddering	1	pass @	BDT 750.00	/pass	BDT 750	BDT 100
Irrigation	15	hr @	BDT 125.00	/hr	BDT 1,875	BDT 251
Threshing	3,143	kg @	BDT 1.25	/kg	BDT 3,929	BDT 526
ZT machine	0.5	pass @	BDT 2,250.00	/pass	BDT 1,125.00	BDT 150.53
Labour operations						
Seeding		p day @	BDT 350.00	/p day	BDT -	BDT -
Fertilising and irrigation	4	p day @	BDT 350.00	/p day	BDT 1,400	BDT 187
Spraying pesticides	4	p day @	BDT 350.00	/p day	BDT 1,400	BDT 187
Harvesting	25	p day @	BDT 350.00	/p day	BDT 8,750	BDT 1,171
			-		-	-
Total costs					**BDT 51,381**	**BDT 6,875**
Gross margins					**BDT 32,820**	**BDT 4,391**

Kharif	**Conservation Agriculture: UPTR Rice**					
Output	**Yield/ha**		**Tk/unit**		**Tk/ha**	**Tk/Bigha**
Rice	5,000	kg @	BDT 17.10	/kg	BDT 85,500	BDT 11,440
Rice straw	5,870	kg @	BDT 2.00	/kg	BDT 11,739	BDT 1,571
Total output					**BDT 97,239**	**BDT 13,011**
Costs	**Rate/ha**		**Tk/unit**		**Tk/ha**	**Tk/Bg**
Seed						
Rice	35	kg @	BDT 35.00	/kg	BDT 1,225	BDT 164
			-		-	-
Fertiliser						
Urea	195	kg @	BDT 16.00	/kg	BDT 3,125	BDT 418
TSP	50	kg @	BDT 22.00	/kg	BDT 1,100	BDT 147
Mop	72	kg @	BDT 14.00	/kg	BDT 1,008	BDT 135
Gypsum	56	kg @	BDT 7.50	/kg	BDT 422	BDT 56
Zinc	6	kg @	BDT 210.00	/kg	BDT 1,172	BDT 157
Herbicides						
Roundup	3	L @	BDT 886.00	/L	BDT 2,658.00	BDT 355.64

			-		-	-
			-		-	-
Pesticides						
Virtako	0.035	kg @	BDT 27,000.00	/kg	BDT 945.00	BDT 126.44
Amistar TOP	0.75	L @	BDT 3,600.00	/L	BDT 2,700.00	BDT 361.26
			-		-	-
Machine operations						
Cultivator		pass @	BDT 1,875.00	/pass	BDT -	BDT -
Wet tillage (puddling)		pass @	BDT 3,000.00	/pass	BDT -	BDT -
Threshing	5,000	kg @	BDT 1.25	/kg	BDT 6,250	BDT 836
Irrigation	25	hr @	BDT 125.00	/hr	BDT 3,125.00	BDT 418.13
			-		-	-
Labour operations						
Seedling raising, uprooting and transplanting	32	p day @	BDT 350.00	/p day	BDT 11,200	BDT 1,499
Fertilising and irrigation	6	p day @	BDT 350.00	/p day	BDT 2,100	BDT 281
Weeding	25	p day @	BDT 350.00	/p day	BDT 8,750	BDT 1,171
Spraying pesticides	6	p day @	BDT 350.00	/p day	BDT 2,100	BDT 281
Harvesting	30	p day @	BDT 350.00	/p day	BDT 10,500	BDT 1,405
Total costs					**BDT 58,379**	**BDT 7,811**
Gross margins					**BDT 38,860**	**BDT 5,199**

Rabi	**Conservation Agriculture, ZT wheat (3 irrig)**					
Output	**Yield/ha**		**Tk/unit**		**Tk/ha**	**Tk/Bg**
Wheat	3,294	kg @	BDT 26.79	/kg	BDT 88,246	BDT 11,807
Wheat straw	7,174	kg @	BDT -	/kg	-	-
Total output					**BDT 88,246**	**BDT 11,807**
Costs	**Rate/ha**		**Tk/unit**		**Tk/ha**	**Tk/Bg**
Seed						
Wheat	120	kg @	BDT 50.00	/kg	BDT 6,000	BDT 803
			-		-	-
Fertiliser						
Urea	260	kg @	BDT 16.00	/kg	BDT 4,166	BDT 557

TSP	100	kg @	BDT 22.00	/kg	BDT 2,200	BDT 294
Mop	108	kg @	BDT 14.00	/kg	BDT 1,512	BDT 202
Gypsum	69	kg @	BDT 7.50	/kg	BDT 516	BDT 69
Zinc	10					
Boron	3	kg @	BDT 460.00	/kg	BDT 1,352	BDT 181
Herbicides						
Affinity	1.5	L @	BDT 1,930.00	/L	BDT 2,895.00	BDT 387.35
Roundup	3	L @	BDT 886.00	/L	BDT 2,658.00	BDT 355.64
Pesticides						
Nativo	0.6	kg @	BDT 6,600.00	/kg	BDT 3,960.00	BDT 529.85
			-		-	-
			-		-	-
Machine/animal operations						
ZT machine	1	pass @	BDT 2,250.00	/pass	BDT 2,250	BDT 301
Irrigation	15	hr @	BDT 125.00	/hr	BDT 1,875	BDT 251
Threshing	3,294	kg @	BDT 1.25	/kg	BDT 4,118	BDT 551
			-		-	-
			-		-	-
Labour operations						
Seeding	0	p day @	BDT 350.00	/p day	BDT -	BDT -
Fertilising and irrigation	4	p day @	BDT 350.00	/p day	BDT 1,400	BDT 187
Spraying pesticides	4	p day @	BDT 350.00	/p day	BDT 1,400	BDT 187
Harvesting	25	p day @	BDT 350.00	/p day	BDT 8,750.00	BDT 1,170.75
			-		-	-
Total costs					**BDT 45,052**	**BDT 6,028**
Gross margins					**BDT 43,194**	**BDT 5,779**

Kharif 1	**Conservation Agriculture, ZT Mungbean**						

Output	Yield/ha		Tk/unit		Tk/ha	Tk/Bigha
Mungbean	1,200	kg @	BDT 68.40	/kg	BDT 82,080	BDT 10,982
Mungbean stover	2,500	kg @	BDT -	/kg	-	-
Total output					**BDT 82,080**	**BDT 10,982**
Costs	**Rate/ha**		**Tk/unit**		**Tk/ha**	**Tk/Bg**
Seed						
Mungbean	30	kg @	BDT 100.00	/kg	BDT 3,000	BDT 401
			-		-	-
Fertiliser						
TSP	90	kg @	BDT 22.00	/kg	BDT 1,980	BDT 265
Mop	44	kg @	BDT 14.00	/kg	BDT 616	BDT 82
			-		-	-
Herbicides						
Roundup	3	L @	BDT 886.00	/L	BDT 2,658	BDT 356
			BDT -		BDT -	BDT -
			-		-	-
Pesticides						
Imidachloprid	0.75	L @	BDT 2,650.00	/L	BDT 1,988	BDT 266
			-		-	-
Machine/animal operations						
Cultivator		pass @	BDT 1,875.00	/pass	BDT -	BDT -
Laddering		pass @	BDT 750.00	/pass	BDT -	BDT -
Irrigation	5	hr @	BDT 125.00	/hr	BDT 625.00	BDT 83.63
Threshing		kg @	BDT 1.25	/kg	BDT -	BDT -
ZT machine	1	pass @	BDT 2,250.00	/pass	BDT 2,250.00	BDT 301.05
Labour operations						
Seeding		p day @	BDT 350.00	/p day	BDT -	BDT -
Fertilising and irrigation	2	p day @	BDT 350.00	/p day	BDT 700.00	BDT 93.66
Weeding	30	p day @	BDT 350.00	/p day	BDT 10,500.00	BDT 1,404.90
Spraying pesticides	8	p day @	BDT 350.00	/p day	BDT 2,800.00	BDT 374.64
Harvesting and threshing	30	p day @	BDT 350.00	/p day	BDT 10,500.00	BDT 1,404.90
Total costs					**BDT 37,617**	**BDT 5,033**
Gross margins					**BDT 44,464**	**BDT 5,949**

Appendix 3 – Site GW extraction statistics

Sites of Analysis

Attached are PDF's which were sourced from the Indian Central Groundwater Development Board (CGWDB), for the following sites. See pdf pages at the end of this report

Karnal, Haryana, India

Varanasi, UP, India

Faizabad, UP, India

Samastipur, Bihar, India

Patna, Bihar, India

Malda, West Bengal, India

Coochbehar, West Bengal, India

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FOR FURTHER INFORMATION

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