FINAL REPORT

Advancing knowledge on the costs and benefits of sustainable soil fertility management in Maharashtra and Madhya Pradesh /India –

a contribution to the project

Soil protection and rehabilitation for food security in India;

An Economics of Land Degradation (ELD) study

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Problem context

The majority Indian rural households depend for their livelihoods on the productivity of the farming systems. Almost universally, the yield gap between potential and achieved productivity is large, water and nutrient use efficiency is low and land degradation can be widely observed (Lobell et al. 2009, Conklin & Stilwell 2007).

Also in the States of Maharashtra and Madhya Pradesh livelihoods of around 65% of the rural population depend on agriculture and related activities. A large share of them are smallholder farmers with often low and unstable crop and livestock productivity. At the same time, land degradation is a major concern also driven by changing cropping patterns. Overall, there has been a steady decline in the area under water efficient crops like groundnut, pigeon pea and other millets. The area under rice and cotton has increased in the recent decades mainly owing to the (over)exploitation of groundwater. Besides, there is indiscriminate use of chemical fertilizers and unbalanced-application of nutrients. Policies subsidizing inorganic fertilizers, particularly N and P also encourage the farmers to rely more strongly on inorganic fertilizer than on organic ones.

Apart from plant nutrition, sustainable soil management requires other management practices for instance to control runoff and erosion, enhance water infiltration, maintain soil organic matter and physical structure. Achieving sustainable intensification through an ecosystem approach is in many cases economically rational taking diverse ecosystem services into account. Such an approach is putting a strong emphasis on input use efficiency and the use of biological inputs (Bommarco et al. 2013).

There is a great potential to adopt ecosystem service smart agricultural technologies and practices. Those can significantly improve the efficiency of water use, the management of soil fertility, carbon sequestration, and last but not least increase yields. Efficient management of soil nutrients can considerably reduce GHG emissions and forms an important part of climate smart and ecosystem service smart agriculture. Integrated nutrient management practices using precision nutrient applications, soil test based nutrient application, crop residues, and inclusion of legumes in the cropping systems have the potential to improve the provision of multiple ecosystem services (Wani et al. 2003, Singh et al. 2014).

General purpose of the project

The objective of this project is to study the impact of cropping system and soil fertility management practices on selected ecosystem services. The study is conducted in the context of semi-arid areas in the States of Maharashtra and Madhya Pradesh in India. It is a direct contribution to the GIZ facilitated NABARD project on Soil protection and rehabilitation for food security in India (SPRFS). Being inspired by the approach of the Economics of Land Degradation Initiative (ELD 2015), this effort adds to a growing data set providing globally relevant data on the economic benefits of land and land based ecosystems.

In order to assess the various intervention strategies on crop yields and farm system performance, we use a combination of (i) empirical data collection (ii) expert knowledge and (iii) crop simulation models parameterized for the locations, to estimate provisioning and regulating ecosystem services which are most strongly affected by cropping and soil management practices. The combination of data sources provides, in a first step, point and farm based estimates of the current farmer practices and the most promising improved agricultural practices. Point/farm based estimates were, in a next step, scaled up on the basis of land use maps to the Mandal level. Comparing different management scenarios allows the estimation of the total impact of alternative management scenarios on diverse ecosystem services.

Ecosystem service impacts were evaluated on the basis of market and shadow prices. Relating these values to the costs of implementing alternative management practices allows to compare costs and benefits on the plot as well as the landscape level.

The study is coordinated by researchers of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). The study is implemented in cooperation with the Foundation for Ecological Security (FES), the Watershed Organisation Trust (WOTR), BAIF Development Research Foundation, the University of Giessen/Germany and the University of Marburg/Germany. The team enjoyed scientific backstopping by a team of the University of Leeds/UK and the Stockholm Environment Institute. The project was cofounded by the CGIAR Collaborative Research Program Water Land and Ecosystems (CRP WLE).

Land Use and Farming System description

The following section will summarize the land use and agricultural management patterns of the project area. The geographic and ecological boundaries of the study area have been set by the NABARD/GIZ project on Soil protection and rehabilitation for food security in India. The study sites in the State of Maharashtra are Bhokardan/Jalna district, Sakri/Dhule district, Parner/Ahmednagar district, Morshi/Amaravati district, and the Asoli, Atmurdi and Devdhari clusters in Yavatmal. In addition, the study will cover the clusters Bichiya and Niwas/Mandla district and Baihar/Balaghat district in Madhya Pradesh.

Methodology Land Use Mapping

In this section, we describe the approach and the data used for the land use and land cover classification covering major crops by season.

Ground survey data was collected during August 19th – 30th, 2016 for 177 sample sites (Figure 1a) and January 19-25th, 2017 for 222 sample sites (Figure 1b covering major cropland areas). The data collection was timed after the rainy season. A minimum sampling unit of 250 m x 250 m for ground truth validation was taken at each location. Observations were recorded while driving and capturing a few more locations for class identification and accuracy assessment.

We looked for contiguous areas of homogeneous land use classes which were considered for sampling. The precise locations of the samples were recorded by a handheld Garmin GPS unit in tracking mode to map the total route traveled. The sample size varied from 15 to 20 samples for each category. For each location we captured photographs using a digital camera (Figure 1a and 1b). Further evaluation was be done during the class identification and labeling. Additional information was gathered from concerned farmers and agriculture officers.

At each location the following information was recorded (e.g.):

1. GPS Coordinates
2. Crop calendar

3. Crop intensity (single, double and triple crops)
4. Planting dates
5. Cropping pattern (Previous/present including season wise)
6. Crop growth / crop health
7. Irrigation techniques/ watering methods: surface irrigated areas

Figure 1a: Field plot data point distribution in the study area during kharif season.

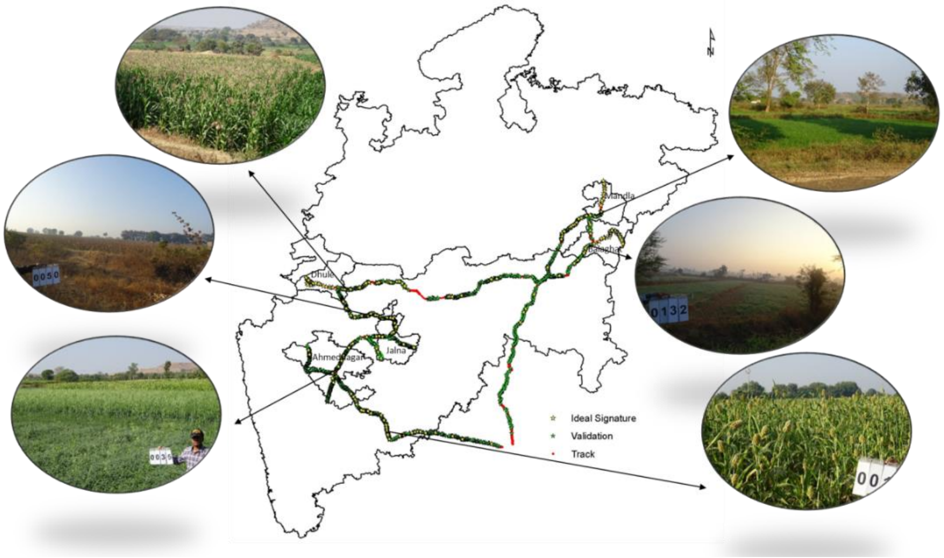
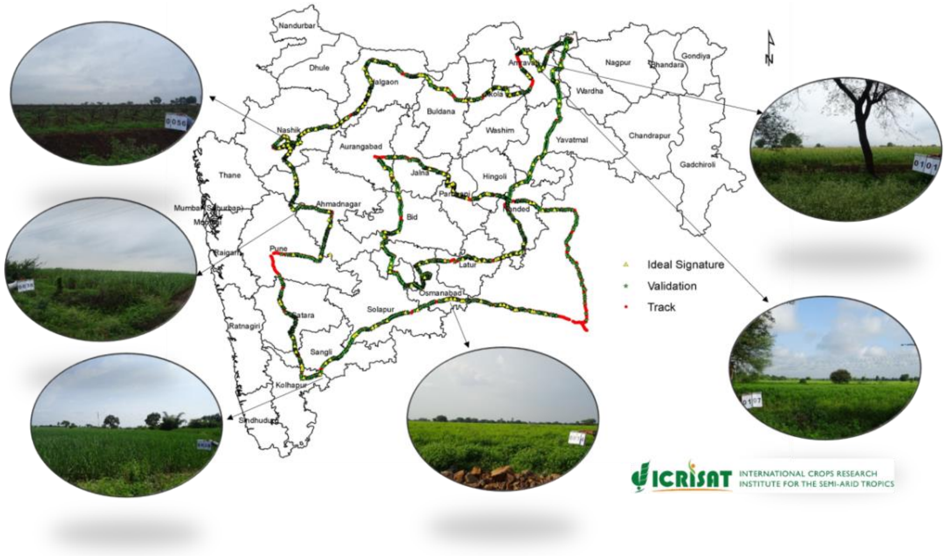


Figure 1b: Field plot data point distributions in the study area during rabi season.



The data was organized in ArcGIS 10.1 and excel file compatible formats with accompanying metadata so as to spatially locate them over the province boundaries (Figure 1a and 1b).

The land use and land cover classification is based on MODIS time series data. An unsupervised ISOCLASS cluster K-means classification was performed to capture the range of variability in phenology in the image. The class identification and labeling process involved the use of the various datasets such as Bi-spectral plots, Ground data, Google high resolution imagery and MODIS time series NDVI signatures. Methods and protocols were adopted from previous studies (Gumma et al. 2011a&b, 2014, Velpuri et al. 2009, Thenkabail et al. 2007).

Accuracy assessment was performed with ground data based on an error matrix as described by Jensen (1996). The error matrix is a multi-dimensional table in which the cells contain changes from one class to another class. The columns of an error matrix contain the field-plot data points and the rows represent the results of the classified land use maps (Congalton 1991 & 2001). The columns of the error matrix represent the actual field information (field-plot data) and the rows of the error matrix correspond to a class in the land use map. The overall classification accuracy was computed as a diagonal point divided by the total number of points. The statistical approach of accuracy assessment consists of different multi-variate statistical analyses. A frequently used measure is Kappa (Cohen 1960), which is designed to compare results from different regions or different classifications. Finally, crop dominance (Figure 2) classification was derived by the above protocols.

Results Land Use Mapping

The analysis of major crop areas in study districts as per the 2013-14 cropping season reveals many important aspects. In all the Maharashtra districts except Ahmednagar, cotton as single crop occupies the highest share ranging from 41% to 13%. After cotton, sorghum, pigeonpea and millets are dominant in all the districts of Maharashtra. Sugarcane is an important crop in Ahmednagar.

The share of single and double crop systems vary over the survey districts. Single and double crops occupy equal share in Amravati district. Single crops dominate Jalna with double crops occupying half of the single crop area. In Yavatmal, single crop system is most dominant. In Ahmednagar district, mixed crops occupy the highest share of land area. Among all the survey districts of Maharashtra, Ahmednagar has good share of shrubs and grasslands.

In the Mandla district of Madhya Pradesh, forests occupy the two thirds area. The dominant crop grown is paddy as single crop followed by millet and maize. In all the districts except Mandla, water bodies occupy less than one percent area. Mandla is richer in water bodies with nearly 2% area. Figures 2a to 2g illustrate the cropping patterns in the project districts.

The advantages of using Modis time series imagery at temporal resolution of every 16-days is that it provides a seasonal profile of the crops grown. This is not possible with other satellite imagery. Also some standardized algorithms are available for cloud contamination during the crop growing season.

Figure 2a: Spatial extent of land use / land cover in Amravati district, Maharashtra state, India. (Note: SC-single crop; DC-double crop)

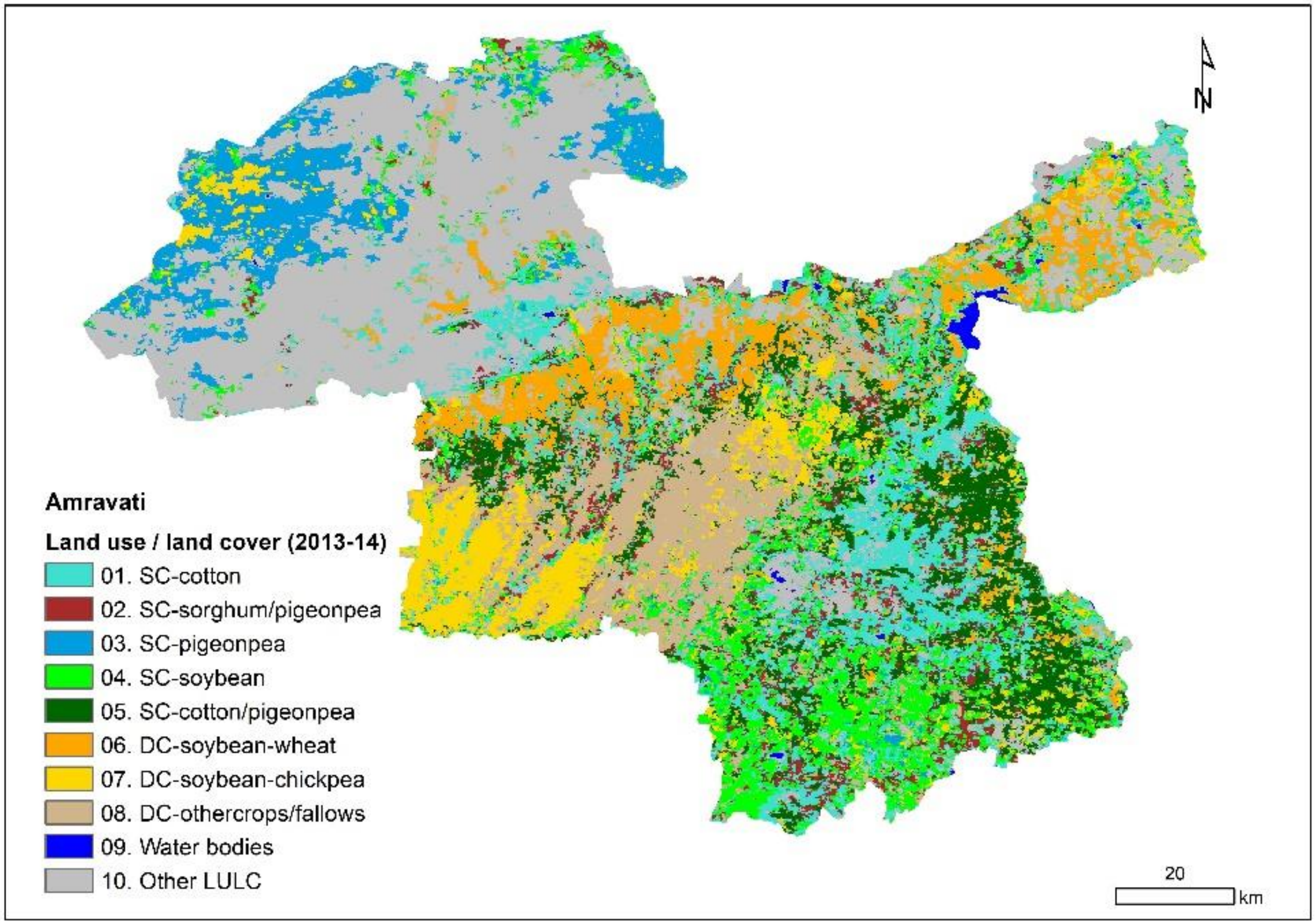


Figure 2b: Spatial extent of land use / land cover in Yavatmal district, Maharashtra state, India. (Note: SC-single crop; DC-double crop)

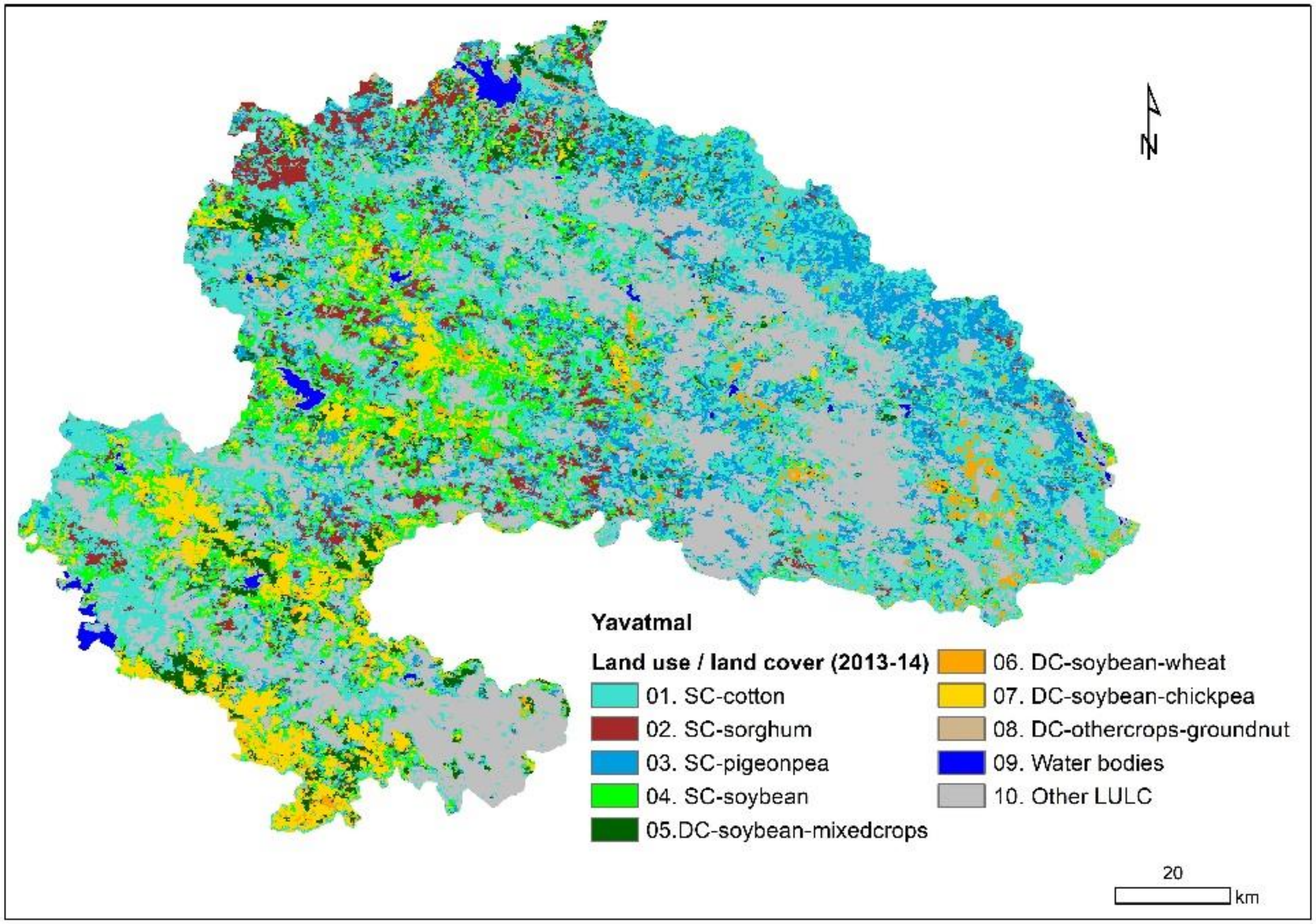


Figure 2c: Spatial extent of land use / land cover in Jalna district, Maharashtra state, India. (Note: SC-single crop; DC-double crop)

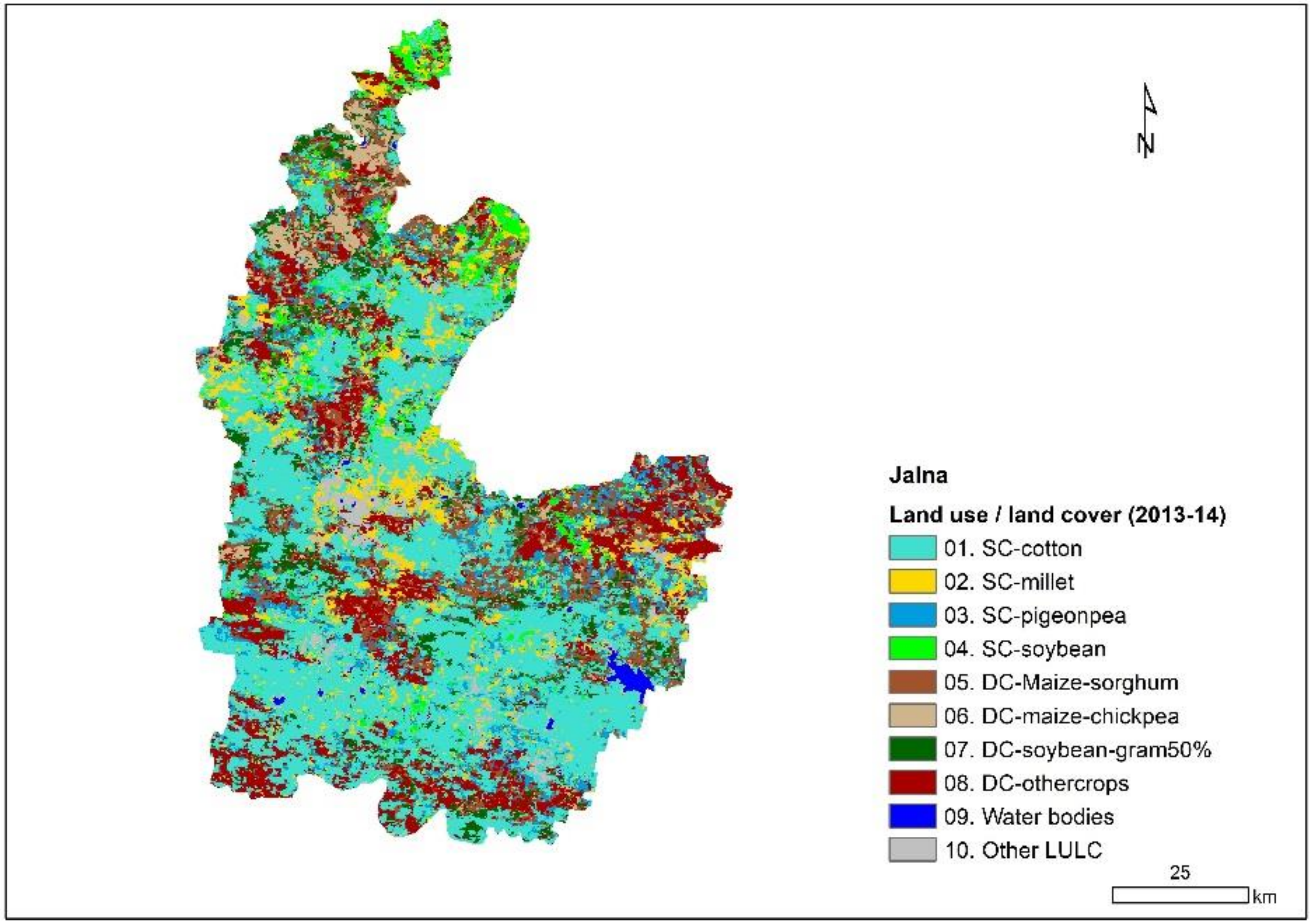


Figure 2d: Spatial extent of land use / land cover in Dhule district, Maharashtra state, India. (Note: SC-single crop; DC-double crop)

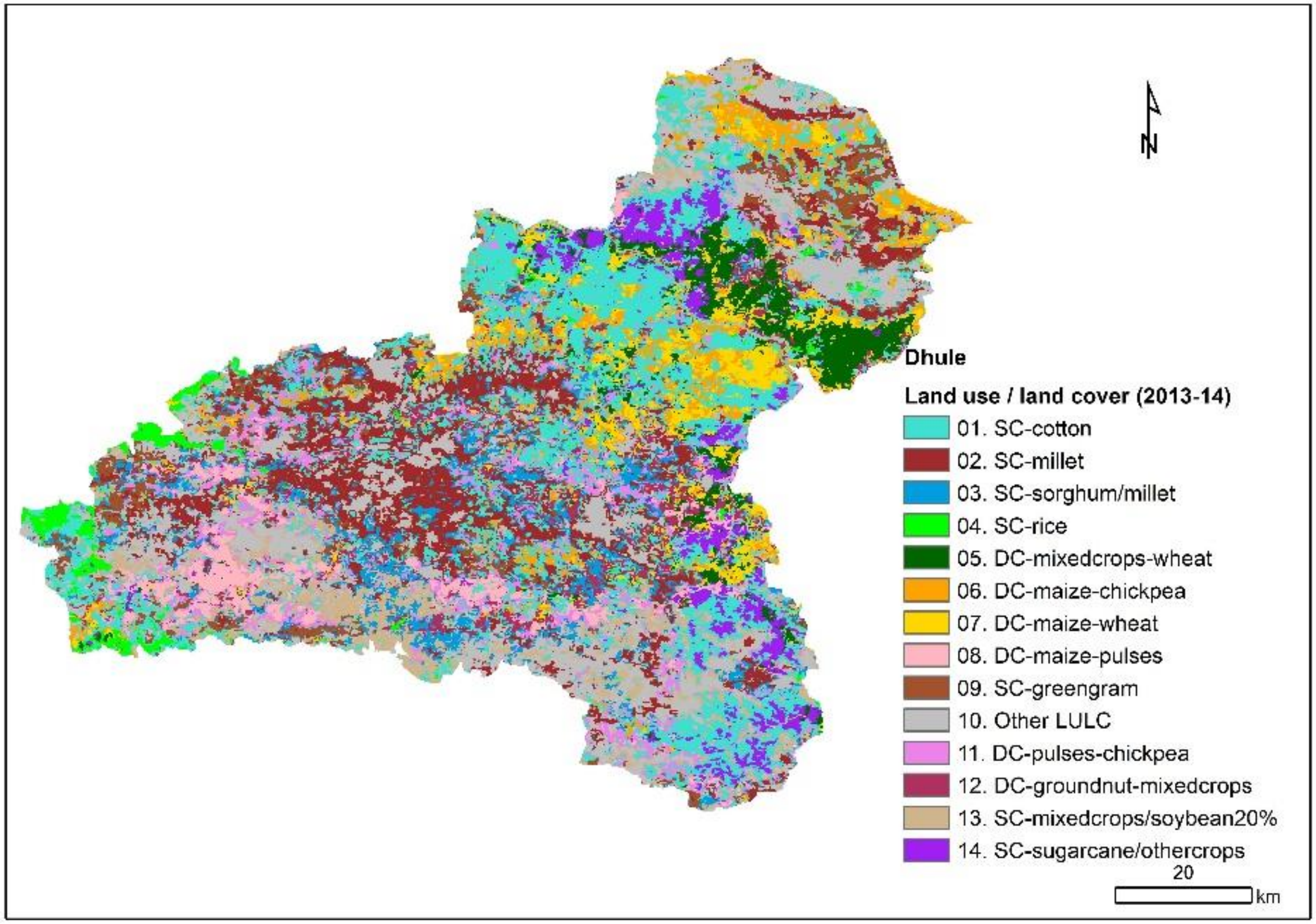


Figure 2e: Spatial extent of land use / land cover in AhmedNagar district, Maharashtra, India. (Note: SC-single crop; DC-double crop)

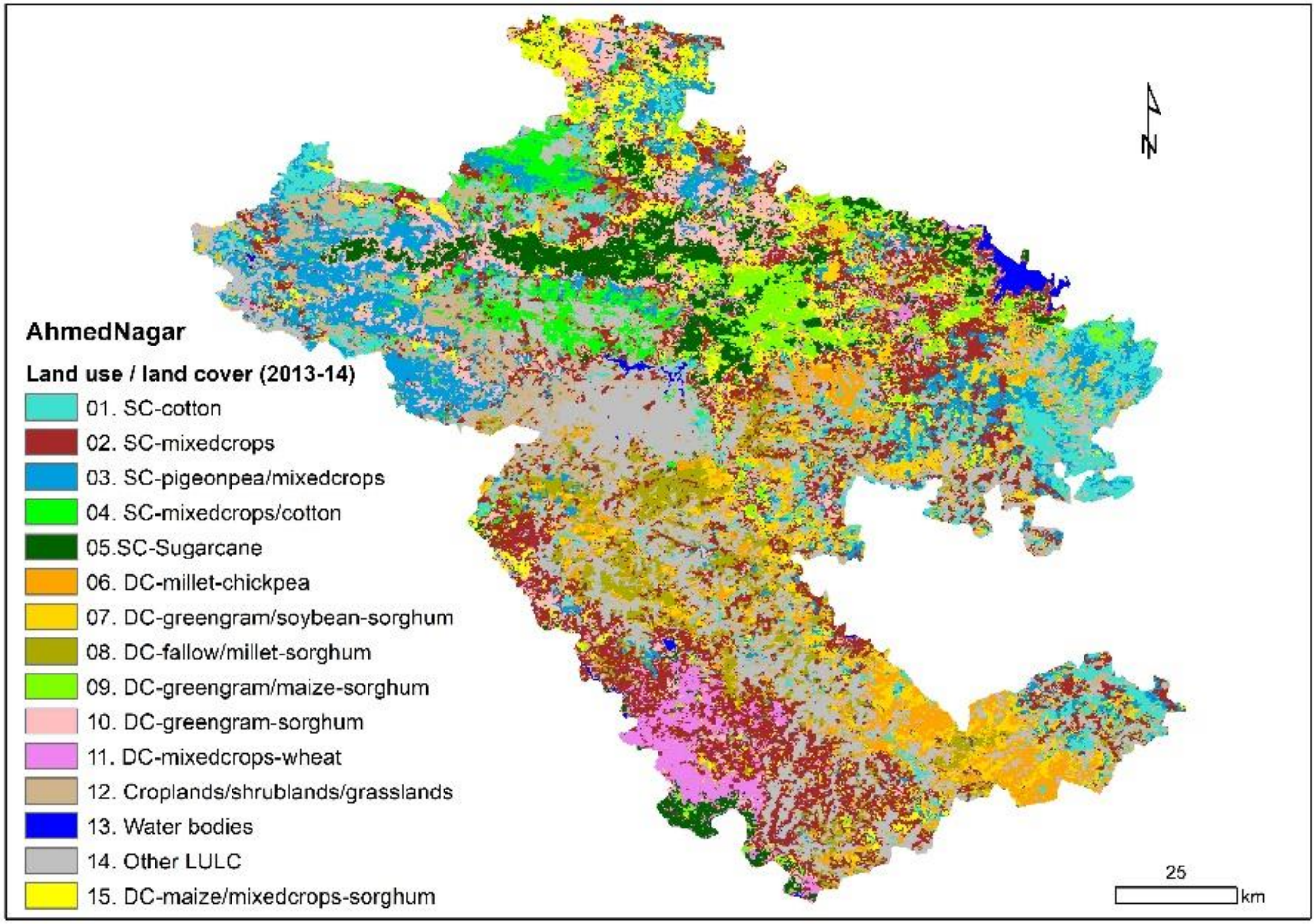


Figure 2f: Spatial extent of land use / land cover in Mandla district, Madhya Pradesh state, India. (Note: SC-single crop; DC-double crop)

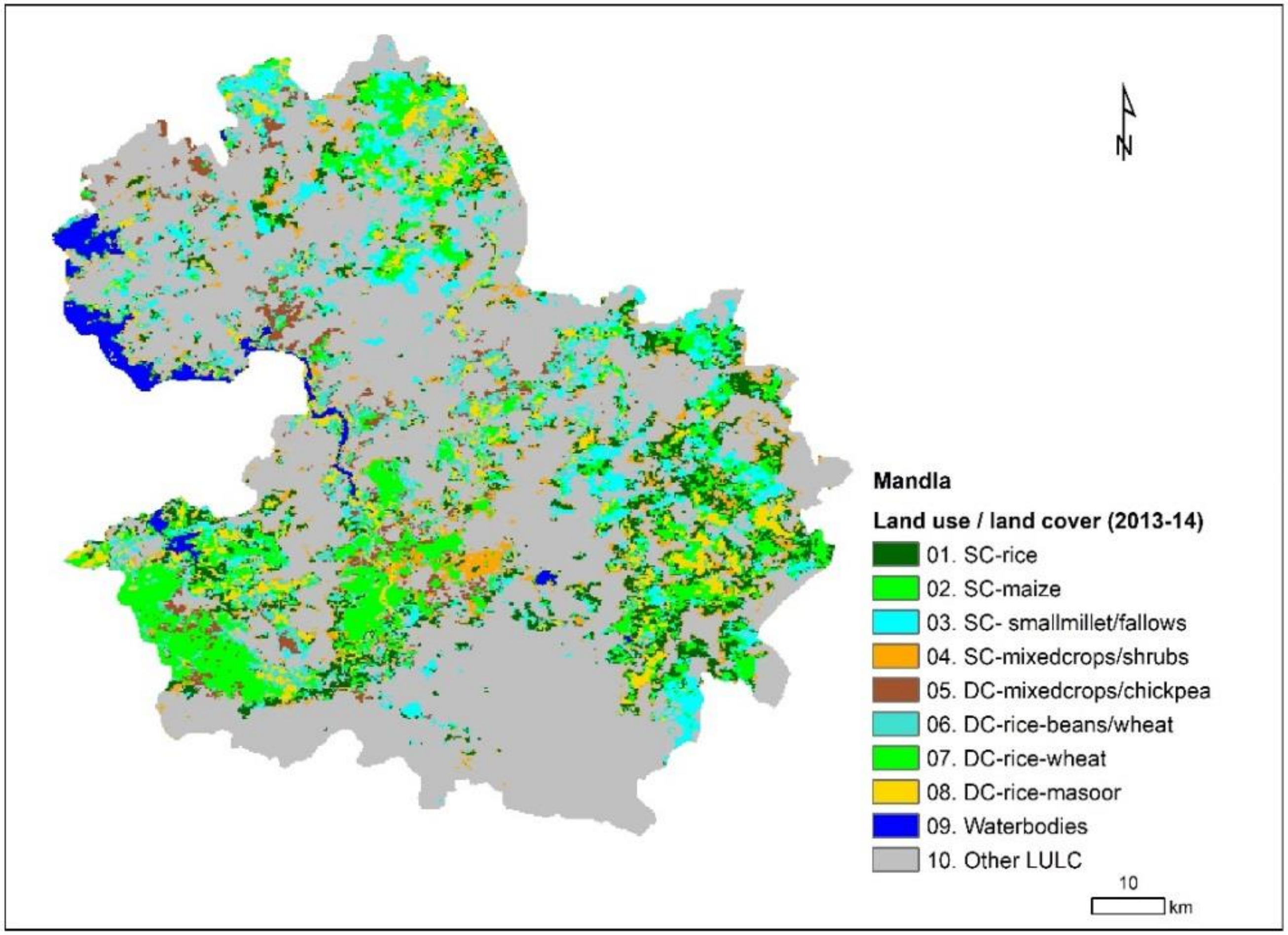
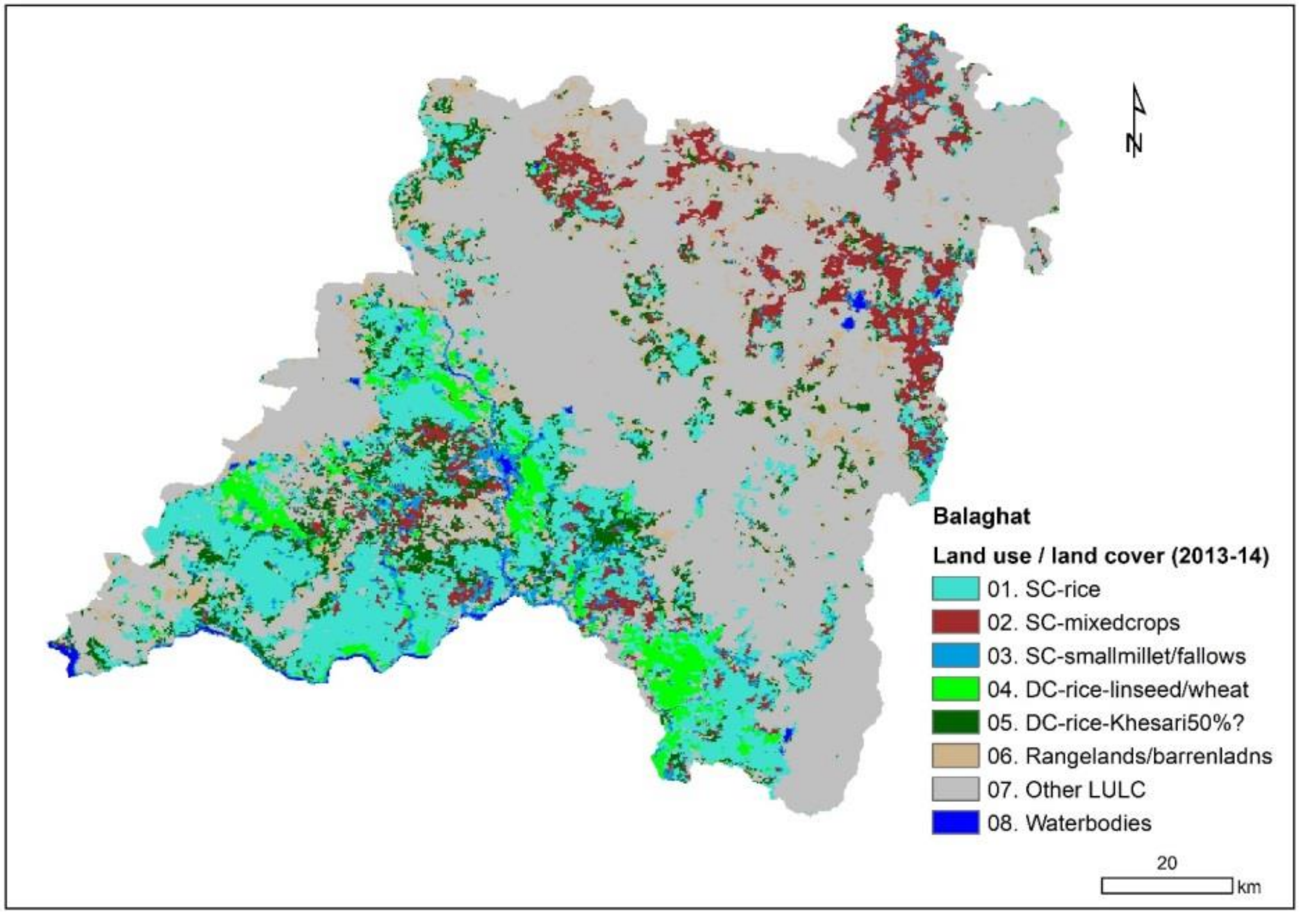


Figure 2g: Spatial extent of land use / land cover in Balaghat district, Madhya Pradesh state, India. (Note: SC-single crop; DC-double crop)



Spectral matching technique along with ground survey data is used for grouping similar classes. There will always be a degree of subjectivity in this grouping process, but extensive field information, local knowledge and ancillary information were all drawn upon to maximize the accuracy of the classification. Some limitations of the products generated are: (a) the resolution of satellite imagery used (MOD13Q1) is 250m, which is bigger than the average small holder farmers in the villages. However, the location of identified crops and cropping pattern is correct to the estimated accuracy. and (b) except for homogeneous cropped areas like rice, sugarcane and cotton which are also irrigated, mixed cropped areas and intercropped areas are identified as they are, since they cannot be separated within the constraints of resolution of the imagery.

Methodology Farming System Analyses

Empirical primary data were collected between October-December 2016 and in July 2017 using transect walk, focus group discussion (FGD) and detailed survey questionnaire. The main objective of all data collection was to better understand the farming systems, to find realistic parameters for the models and to validate the models.

Transect walks were carried out in seven villages with key stakeholders of the communities with the objective to understand the agro-ecological systems. Seven focus group discussions (FGD) with the key stakeholders were conducted in the same villages though people from nearby villages also joined. The main objectives of FGDs were to understand cropping systems, current agricultural practices, major constraints related to agriculture, and farmers' aspirations.

A questionnaire for an in depth household survey was prepared. It included information related to:

1) household assets (land, machinery, livestock, financial assets and liability),
2) household income,
3) the food security situation,
4) access to value chains,
5) social capital,
6) climatic adaptation and adaptive capacity of the household,
7) cropping and livestock systems,
8) major climatic constraints,
9) level of mechanization,
10) adoption of climatic smart practices (recent 5 to 10 years), and
11) access to agricultural and climatic information.

A pre-test of the structured interviews was done in ten households and necessary changes were made. A total of 160 households were selected in the eight SPRFS project clusters based on information of the cooperating NGO experts. The selection was done in a way that it covered farmers within different land size groups, households benefiting from direct interaction with the NGOs and households not directly interacting with them. It was further important to include some farmers who manage private farm ponds. We have to emphasize that we do not claim that our sample is representative for the overall districts. It was more important for us to capture the diversity of farming systems in the areas where the SPRFS project is active.

Secondary data sources such as National Bureau of Soil Survey & Land use Planning (NBSS & LUP), Nagpur, National Innovations in climate Resilient Agriculture (NICRA), Hyderabad, have been used for soil type and rainfall variables respectively. Our survey data have been further compared with the Census of India and Agriculture census of India.

Results Farming System Analyses

Table 1 summarizes the average rainfall and soil type of the 6 districts in which the project clusters fall. Farming systems in the project area strongly determined by the soil type and fertility as well as the climatic conditions. Overall, the soils in the project area are low in available nitrogen, medium to high in available phosphorus and medium to high in available potassium. They are found to be deficient in micronutrients, zinc and boron to the extent of 10-40%.

Table 1: Average rainfall and soil type in project districts; source: http://www.nicra-icar.in**,** http://nbsslup.in

District	Project clusters	Average annual rainfall (mm)	Soil Type
Ahmednagar	Parner	562	Shallow grey (65.4%), Medium deep black (23.9%), Deep black (10.7%)
Jalna	Bhokardhan	750	Deep black (13.4%), Medium deep black (21.4%), Shallow black (65.2%)
Dhule	Sakari	729	Shallow black (59.8%), Medium deep black (23.9%), Deep black (16.3%)
Amravati	Morshi	886	Deep black (55.9%), Medium deep black (1.2%), Shallow black (42.9%)
Yavatmal	Ralegaon	886	Deep black (34.7%), Medium deep black (13.0%), Shallow black (52.3%)
Mandla	Bicchiya & Niwas	1445	Deep Soil (22.9%), Medium Deep (21.3%), Shallow soils (55.8%)

Table 2 summarizes the household characteristics by project clusters in Maharashtra and Madhya Pradesh. There is a low variation in average family size among the project clusters. Families are slightly smaller in Ahmednagar/Maharashtra with only five members whereas the households in Moccha/ Madhya Pradesh have 7.5 family members. The family size is in a similar range as reported in the Census of 2011 (RoI 2011b).

Household heads in the Maharashtra districts of Amravati, Jalna and Yavatmal enjoy higher education with on average nine years of schooling. Household heads in Bicchiya and Niwas are on average less educated. These findings are again in line with the National Census statistics (RoI 2011b). The difference in literacy rate in male and female is less in Amaravati cluster (7.6 %) and is high in Jalna (20.5 %).

The average size of own land holding, average operating land holding, land values, livestock per household and value of livestock is summarised in Table 3. Land holdings depend both on agro-ecological and wealth conditions. We observe a strong heterogeneity across our clusters even within the states. Yavatmal households operate on average 8.7 acres and own on average 7.2 acres. Even though Dhule is situated in a similar environment, households here operate and own on average only 3.2 acres. Households in Jalna report on average the largest irrigated land availability. This number is lowest for the high rainfall areas of Bicchiya and Niwas. The land values per acre range from above INR 300,000 in Moccha to INR 85,000 in Jalna. Irrigated land values range between INR 700,000 in Jalna and INR 60,000 in Bicchiya and Niwas.

Table 2: Household characteristics by cluster in Maharashtra and Madhya Pradesh

Cluster	Project survey sample size	Average family size of project survey	Average family size of project cluster (Census of India 2011)	Average years of education of household head	Literacy Percentage in project cluster (Census of India 2011)		
					Male	Female	Overall
Ahmednagar	20.0	5	5	7	74.3	59.8	67.2
Amravati	10.0	7	4	9	81.7	74.1	78.0
Dhule	20.0	6	5	6	61.5	48.3	55.0
Jalna	20.0	6	5	9	69.6	49.1	59.8
Yavatmal	30.0	6	4	9	79.2	69.4	74.4
Bicchiya & Niwas	40.0	5	4	3	65.3	45.6	55.4
Moccha	20.0	8	4	4	65.3	46.0	55.6

Farmers in Ahmednagar, Dhule and Moccha own around ten livestock per household. Livestock population is less in other clusters. Accordingly, the value of livestock is highest in Ahmednagar with INR 120,000 per household whereas it is only around INR 60,000 to 70,000 in Dhule and Moccha clusters. Livestock ownership is lowest on Amravati (Table 3).

Table 3: Land and Livestock assets by cluster in Maharashtra and Madhya Pradesh

Cluster	Average size of own land holding in acre (GoI 2011b)	Average size of own land holding in acre in project survey	Average size of operating land holding in acre of project survey	Irrigated own land (acre)	Land value (INR/ acre)	Livestock per household	Total value of livestock in INR
Ahmednagar	3.5	5.7	5.8	3.6	215,000	11	122,047
Amravati	4.1	4.5	5.3	2.3	290,000	2	8,000
Dhule	4.6	3.2	3.3	2.1	140,000	10	72,315
Jalna	3.3	6.5	7.0	5.6	85,000	4	56,211
Yavatmal	5.7	7.2	8.7	3.5	205,000	6	60,374
Bicchiya & Niwas	4.0	4.7	4.7	1.1	143,145	5	25,571

Moccha	5.0	5.2	5.8	1.6	311,000	205,000	10	62,958

The share of households having access to different types of agricultural equipment is summarized in Table 4. Our analysis indicated that the sample respondents in Yavatmal cluster have the best access to machinery and tools. The lowest level of access to machinery was observed in Bicchiya and Niwas.

Table 4: Percentage of households having access to agricultural equipment by project clusters in Maharashtra and Madhya Pradesh

Cluster	**Bullock cart**	**Drip irrigation/ Sprinkler set**	**Electric motor/ Diesel pump set /Oil engine**	**Sprayer**	**Thresher**	**Tractor**	**Others**
Ahmednagar	35	60	90	45	0	15	100
Amravati	10	10	50	60	0	0	100
Dhule	45	10	65	35	0	0	100
Jalna	45	75	90	75	10	10	100
Yavatmal	67	53	77	87	3	3	100
Bicchiya & Niwas	0	0	0	13	0	0	100
Moccha	45	0	45	10	0	15	100

The access figures fit only partially to the responses regarding the levels of mechanization. The respective results are summarized in Table 5. Across most clusters, the highest level of mechanization is reported related to land preparation and threshing. Mechanisation is significantly lower at the Madhya Pradesh sites. Especially in the Bicchiya and Niwas clusters this can also be explained with poor access to equipment. Another reason may be the aforementioned smaller plot sizes. In all the clusters, sowing, spraying of pesticides, insecticides and weedicides, weeding as well as harvesting are either not done or done mostly manually.

Table 5. Percentage of households using mechanisation in agricultural operations in Maharashtra and Madhya Pradesh project clusters

Cluster	Land preparation	Sowing	Spraying	Weeding	Harvesting	Threshing
Ahmednagar	80	15	10	0	0	100
Amravati	70	10	0	0	0	90
Dhule	35	0	0	0	0	75
Jalna	90	5	0	0	5	100
Yavatmal	45	0	3	0	21	86
Bicchiya & Niwas	10	2.5	0	0	0	5
Moccha	25	0	0	0	0	20

Table 6 summarizes the average number of sources of income per household, their financial assets and liabilities in terms of average borrowings, lendings and savings per household in INR. The respondents in both Maharashtra and Madhya Pradesh are net borrowers. Borrowings are highest in Jalna (INR 150,000) and lowest in Bicchiya and Niwas (INR 4,600). The net savings are ranging from INR 20,000 in Ahmednagar to INR 3,000 in Bicchiya and Niwas. Livelihoods are diversified even though agriculture is the primary occupation.

Table 6: Number of income sources, borrowings, lending's and savings (Rs) per household by cluster in Maharashtra and Madhya Pradesh

Cluster	No. of sources of income	Borrowings (Rs)	Lending (Rs)	Savings (Rs)
Ahmednagar	2.8	101531	5600	20379
Amravati	2.4	38133		12358
Dhule	3.3	106636	10000	6440
Jalna	2.6	147739	10000	17765
Yavatmal	2.6	110467	4000	11867
Bicchiya & Niwas	4.1	4627	1002	3486
Moccha	4.3	76109	7000	15222

Respondents report drought as most sever natural constraint in the Maharashtra villages. The frequency of occurrence of drought is perceived to be four times out of ten years and it is reported to reduce crop yields by up to 77 percent. The second major constraint are pests and diseases. In cotton growing districts (Jalna, Amravati and Yavatmal), lalya is a major problem resulting in up to 50 percent loss in yield. Water logging is another challange in Amravati and Yavatmal districts. The Amravati district has a fifty percent black soil share which has a higher water holding capacity. In years of very high rainfall this leads to reduced crop yields.

In Madhya Pradesh villages, drought are reported two to three times in ten years reducing crop yields by 40%. Temperatures go very high in this region resulting in yield losses of up to 70% in certain years. Wild boars are a major cause of yields losses. The project villages in this area are close to forests.

Farmers report changes in cropping pattern over the last decade. Many Ahmednagar farmers have shifted from traditional food crops like pearl millet and sorghum to more profitable vegetable crops such as onion. In Amravati and Yavatmal, farmers are cultivating pigeon pea, cotton, or soybean, cotton intercrops. The area under soybean and cotton fluctuates. Farmers cultivate soybean after three to four years of cotton for crop rotation. Farmers with irrigation facility, often choose soybean in kharif and wheat in post rainy season.

The area under finger millet declined in Dhule district due to low yields and was replaced by paddy. For the same reason, the area under the pearl millet crop is reduced in Jalna district. It was according to our respondents largely replaced by cotton and maize. In Madhya Pradesh, the area under millets also declines and is replaced by paddy. In this case more frequent cases of extreme rainfall events and untimely arrival of the monsoon were mentioned as main reasons.

Perceptions on ecosystem services related to agricultural fields

Communities all around the world make strong use of a wide range of natural resources. They benefit from ecosystem services (ESS) as aspects of ecosystems which are utilized to produce human well-being (Fischer et al. 2009). In particular poor smallholders depend on provisioning ESS such as food, fuel, grazing biomass, timber, and medicine (Sukhdev 2009). In addition, the poor are the group most vulnerable to ecosystem disservices (EDS) such as pest infestation or river flooding. Ecosystems further provide regulating and cultural ESS which are experienced by multiple beneficiaries on the local, regional and global scale (MEA 2005, Raudsepp-Hearne et al. 2010).[1] The social and ecological interactions relevant to the governance of ESS and EDS are, however, not yet sufficiently understood (Reyers et al. 2013). Different actors are still challenged to find ways of managing ecosystems which strike a balance and enhance the provisioning of ESS while limiting the occurrence of EDS.

Alternative management choices at various scales lead to different constellations of actually and potentially provided ESS and EDS.[2] Often there are trade-offs where optimizing one ESS provision results in gains and losses of other ESS (Tallis et al. 2008). Insufficient knowledge about ESS-EDS interactions in combination with institutions failing to take externalities into account often results in suboptimal decisions favouring the provision of some ESS at the expense of losses of other ESS or increase of EDS (Rodriguez et al. 2006).

In this step of our study we assessed the perceptions of stakeholders on the provision of ecosystem services. This will help to better understand the rationales and priorities with regard to agricultural management. Our starting point is the acknowledgement that ESS differ in their characteristics, and we use this as a vehicle to link ecosystem services to different social system dimensions (Fisher et al. 2009). We classify the ESS in order to draw conclusions on governance challenges related to the ESS.

Methodology of assessment of perceptions on ESS

For the purpose of this study we have collected farmer' and expert opinions on the provision of ecosystem services related to agricultural fields. We openly asked approximately 50 farmers during seven Focus group discussions which gifts and burdens they experience in relation to their fields. The same question was given to approximately 30 participants of a National Workshop of the Economics of Land Degradation Initiative in India held in Delhi on 2nd December 2016. The participants represented a wide range of organisations such as the UN Environmental Programme, the National Bureau of Soil and Land Use Survey, the National Bank for Agriculture and Rural Development (NABARD), a wide range of NGOs (e.g. FES, WOTR, BIAF, WWF) and diverse research institutions (e.g. TERI Institute, Indira Gandhi Institute of Development Research, International Water Management Institute).

We classify the ESS mentioned by different stakeholders into private, public and toll goods as well as common pool resources based on their characteristics of excludability and subtractability (Ostrom 2009).

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[1] Following the argument of avoiding double counting we do not look specifically into supporting ESS (MEA 2005, Maynard 2015).

[2] For the remainder of this paper we will consider ESD as ESS losses and therefore talk about ESS gains or losses when addressing ESS and ESD.

This is a clearly defined classification system which supports our understanding of the conditions under which specific institutions can prevent ESS degradation (Carpenter et al. 2009). To be effective, institutional frameworks need to be developed which best fit to different types of ESS (Fisher et al. 2009). The information on ESS characteristics have been analysed in a descriptive way using visualizations.

Results of assessment of perceptions on ESS

Figures 3a & b summarize the results of the ESS perception assessment. Our results indicate that farmers acknowledge most strongly private goods provided by agricultural fields. In contrast, the diverse expert

Figures 3a & b: Mapping ESS on the characteristics of excludability and subtractability

group represented in the ELD workshop collected a larger number of benefits which can be classified as public goods. Overall 33 ecosystem services were mentioned. It should be noted that there are overlaps between the mapped ecosystem services. The list would have to be cleaned for any evaluation in order to avoid double counting.

Discussion

The discussion around agricultural fields is typically dominated by outputs such as food production and income generation. The consulted stakeholders reveal an awareness for a much greater diversity of benefits. Even when taking double counting into account, the list of services is impressive. This alone might call for an adjustment of agricultural policies. Natural resource governance studies often focus on a single resource used by a single user group. ESS research teaches us, however, that basically ecosystems – including cultural landscapes of cultivated land - provide multiple potentials for generating a broad range of benefits to people (e.g. OECD 2003, MEA 2005, Maynard et al. 2014, IPBES 2015). It remains a challenge to understand and indeed manage such situations (Kosoy & Corbera 2010, Hinkel et al. 2015, Ruckelshaus et al. 2015).

It is not surprising that farmers are more aware of ESS which can be classified as private goods. They can most easily benefit from such services because it is much easier to exclude somebody from the enjoyment. The stakeholders participating in our ELD workshop in Delhi represented organizations which are more concerned about the overall wellbeing of the society. Many of the ESS listed by them benefit people at larger scales.

For disentangling governance challenges related to different types of ecosystem services we first of all distinguish between (1) provisioning action situations where beneficiaries create, maintain, or improve an ESS, and (2) appropriation action situations where actors subtract from a stock of ESS (Hinkel et al. 2015). The interaction of these action situations critically affects the natural resource management (Cole et al. 2014). There is a risk that incentives for short-sighted resource-use decisions lead to suboptimal outcomes from a wider local, regional or global social welfare perspective. We call such incentive constellations social dilemmas. They are more likely when public goods and common pool resources are affected (e.g. Costanza et al. 2011) and often lead to an over-exploitation of the ecosystem service potential and/or under-investment into underlying ecosystem functions and service potentials. Identifying ESS related social dilemmas is a prerequisite for developing more effective governance mechanisms in agriculture.

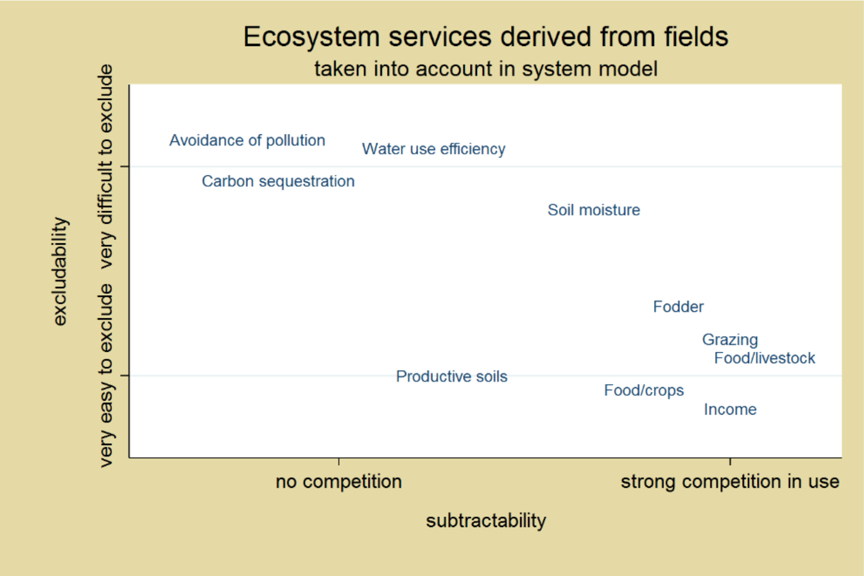
In our specific case, the farmers' management affects the provision of public goods which are enjoyed by people who are often not contributing to its generation. Our perception assessment confirms that farmers are little aware of such benefits and therefore often do not take them into account in their management decisions. Awareness raising could be one reaction to this situation. Another policy response would be to reward farmers for choosing practices which increase the provision of public goods. Such incentives could be understood as payments for ecosystem services rather than as subsidies.

Any such policy instruments requires, however, to know which practice is affecting which ecosystem service in which context. This is our motivation to estimating ecosystem services related to farming. In a next step we will introduce our methodology for this estimation.

In the frame of this project we will not be able to take the full range of services into account. First of all we removed some ESS in order to avoid double counting. Secondly, cultural ESS are neglected as the focus is on field based interventions which do not imply fundamental land use changes. The impact of the promoted practices on cultural ESS is at best moderate. Thirdly, we focused on selected provisioning and regulating ESS which can best be estimated using our crop modelling approach. Our selection still covers a considerable diversity of ecosystem services in terms of good types. We further focused on ecosystem services which are strongly affected by the management practices promoted by the SPRFS project.

The fact that not all ESS acknowledged by stakeholders are taken into account should be considered when interpreting the results. Figure 4 maps the ESS estimated in our study based on their characteristics of excludability and subtractability.

Figure 4: Mapping the ESS estimated in the ELD India study



Estimating the impact of agricultural practices on ecosystem service provision

The States of Maharashtra and Madhya Pradesh in India are having large area of drought-prone agricultural land in India. Livelihoods of around 65% rural population are dependent on agriculture and allied activities. Severe land degradation, low and unstable crop and livestock productivity are the major characteristics of smallholder rainfed (dryland) agriculture. Overall, there has been a steady decline in the area under water efficient crops like groundnut, pigeon pea and other millets whereas, the area under rice and cotton has increased in the recent decades mainly owing to the (over)exploitation of groundwater. The soils in the project target area are low in available nitrogen, medium to high in available phosphorus and medium to high in available potassium. They are also found to be deficient in micronutrients, zinc and boron to the extent of 10-40%. Besides, there is indiscriminate use of chemical fertilizers not based on the results of soil tests at individual farm level leading to over/under or unbalanced-application of nutrients. Policies subsidizing inorganic fertilizers, particularly N and P also encourage the farmers rely more on inorganic fertilizer than on organic ones

There exists a great potential to adopt ecosystem service smart agricultural technologies and practices that improve the efficiency of the use of ecosystem services such as water and soil fertility and to improve the capacity of ecosystems to provide multiple services. This can lead to not only increased production but reduced GHG emissions and enhanced carbon sequestration. Scientific management of soil nutrition for higher nutrient use efficiency and thereby reduced GHG emissions can form an important part of both a climate smart and ecosystem service smart agriculture. Integrated nutrient management practices using precision nutrient applications, soil test based nutrient application, crop residues, and inclusion of legumes in the cropping systems have the potential to improve the provision of multiple ecosystem services

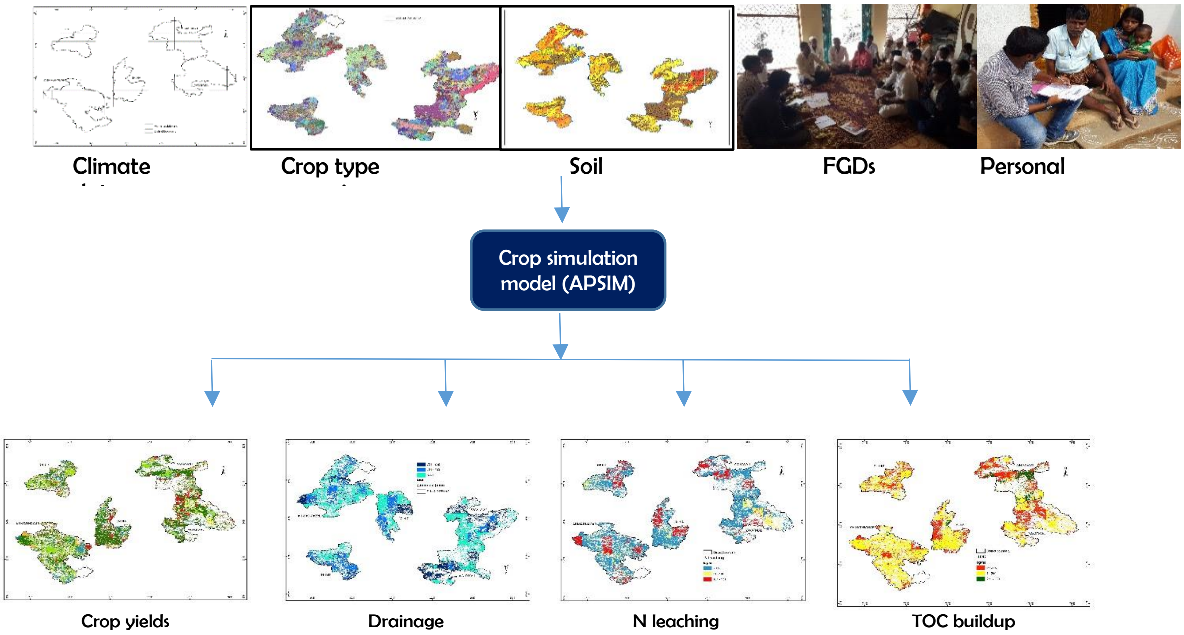
The objective of this specific project was to study the impact of cropping system and soil fertility management practices on selected ecosystem services in semi-arid regions of Maharashtra state of India. The study was a direct contribution to the GIZ facilitated project on Soil protection and rehabilitation for food security in India (SPRFS). Using the well tested 6+1 approach of the Economics of Land Degradation Initiative (ELD 2015), this effort added a growing data set providing globally relevant data on the economic benefits of land and land based ecosystems.

The proposed study was conducted based on the framework set by the SPRFS project and in close collaboration with the implementing partners of the SPRFS project. The study sites in the State of Maharashtra were Bhokardan/Jalna district, Sakri/Dhule district, Parner/Ahmednagar district, Morshi/Amaravati district, and the Asoli, Atmurdi and Devdhari clusters in Yavatmal.

Methods and data of ESS estimation

The following section will give an overview of the modelling process. It will briefly describe the steps of estimating ecosystem service values based by the use of APSIM crop models. The data used as basis for the modelling will be summarized. Figure 5 illustrates the process.

Figure 5. Overview of methodology followed in estimation of ESS parameters



Biophysical modeling

Once after the crop type maps were obtained we used the process based model such as APSIM to simulate the crop yields in particular grids where a particular crop is grown. We also evaluated various benefits from the soil fertility enhancing technologies project outputs under both current and future climates of the target grids of 5 districts in Maharashtra.

The major components of these models were vegetative and reproductive development, carbon, water and nitrogen balance. The models simulated crop growth and development using a daily time step from sowing to maturity and ultimately predicted yield. Genotypic differences in growth, development and yield of crop cultivars are affected through genetic coefficients (cultivar-specific parameters) that were input to the model in addition to crop-specific coefficients that were considered less changeable or more conservative in nature across crop cultivars.

The physiological processes that were simulated describe the crop response to major weather factors, including temperature, precipitation and solar radiation and include the effect of soil characteristics on water availability for crop growth. Soil water balance was a function of precipitation, irrigation, runoff from the soil surface, soil evaporation, transpiration and drainage from the bottom of the soil profile. Daily surface runoff of water was calculated using the U.S. Department of Agriculture (USDA), Soil Conservation Service curve number technique (Soil Conservation Service 1972). For computing soil water drainage, the model used a ‘tipping bucket’ approach when a layer’s water content is above a drained upper limit (DUL).

In the model, high temperature influences growth and development and allocation of assimilates to the reproductive organs was reduced by decreased pod set and seed growth rate. The model's prediction of elevated temperature effects on pod yield were tested and shown to predict well against elevated temperature data. Increased CO2 concentrations in the atmosphere increased crop growth through increased leaf-level photosynthesis, which responds to CO2 concentration. The models needs extensive parameterization and calibration before they can be put in to use. So we useed AICRP (All India Coordinated Research project, ICAR) trials data to calibrate the simulation models

Long term spatial Climate data

The long term trends in observed seasonal precipitation and temperature over Maharashtra using IMD along with AgMERRA gridded rainfall and temperature at daily time scales has been performed to arrive at current baseline climatology for the time period 1980-2009 (30 years).

Soil input data

For each grid cell, soil inputs to the model were obtained from a set of 90 soil profiles developed by blending and interpreting information from crop modeling studies conducted in India in various location and WISE database (Batjes, 2009). We also used the soil profile data sets developed by NBSSLUP for the state of Maharasthra. Simulations were run for all soils in each grid cell, and the cell-specific output was computed from the area-weighted average based on the area share of each soil in the grid cell.

Planting and crop management.

We adopted automatic planting procedure available in simulation models. We triggered the planting event of rainfed crops whenever the cumulative rainfall after the onset of monsoon reaches 50 mm. other crop management practices were obtained from the survey data collected from the farmers in the study region.

Integrated packages

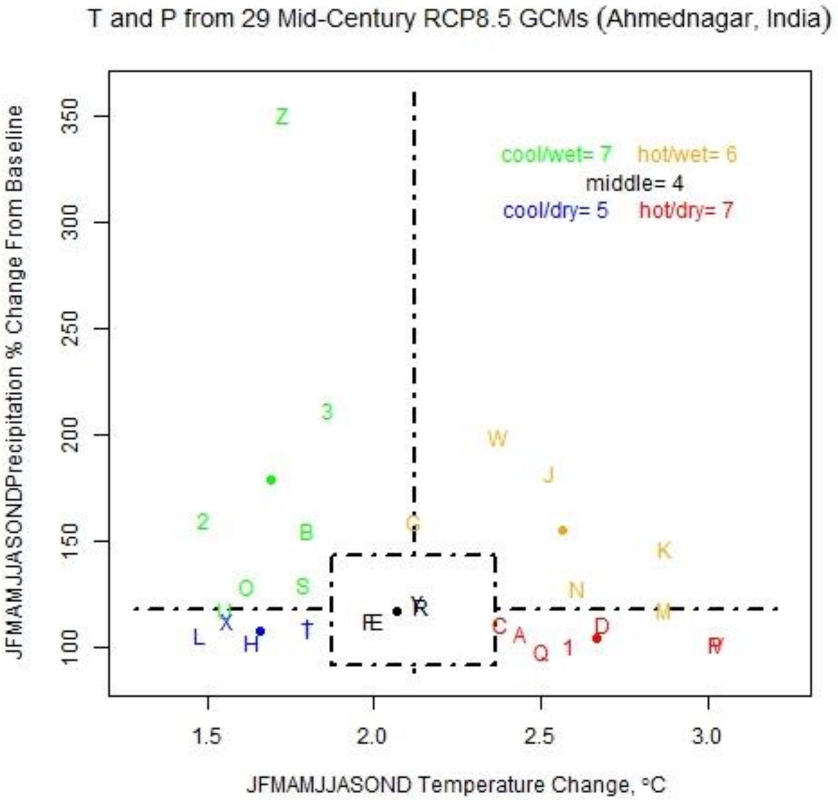
The integrated packages include application of three tons of farm yard manure every year for rainy season crop, recommended nitrogen fertilizers for both rainy and post rainy season crops plus promotion of farm ponds and application of one strategic irrigation from the water collected from farm ponds. In the present study we compared all the parameter with farmers practices (management data as collected from household survey) Vs integrated practices as explained above.

Climate scenarios

We identified location specific fundamental classes of projected climate change. We characterized an individual model's projected, location-specific temperature and precipitation changes in terms of its deviation from the ensemble median. Accordingly we identified five individual GCMs that capture a profile of the full ensemble of temperature and precipitation change with the annual season to select the five climate models out of 29 GCMs. A scatter plot (Figure 6) was generated to represent climate models with their magnitude of future change. In the scatter plot represents cool/wet, hot/wet, cool/dry and hot/dry models relative to the median of the model spread.

In this study we simulated the impact of the hot-dry and cool-wet scenarios which are closest to the median. Both scenarios are warmer compared to the baseline with the hot-dry being hotter than the cool-wet one. The precipitation of the hot-dry scenario is only slightly above the baseline. It is significantly higher under the cool-wet scenario.

Figure 6: Selection of GCMs for the study region (Maharashtra) using the precipitation and temperature change scatter plot

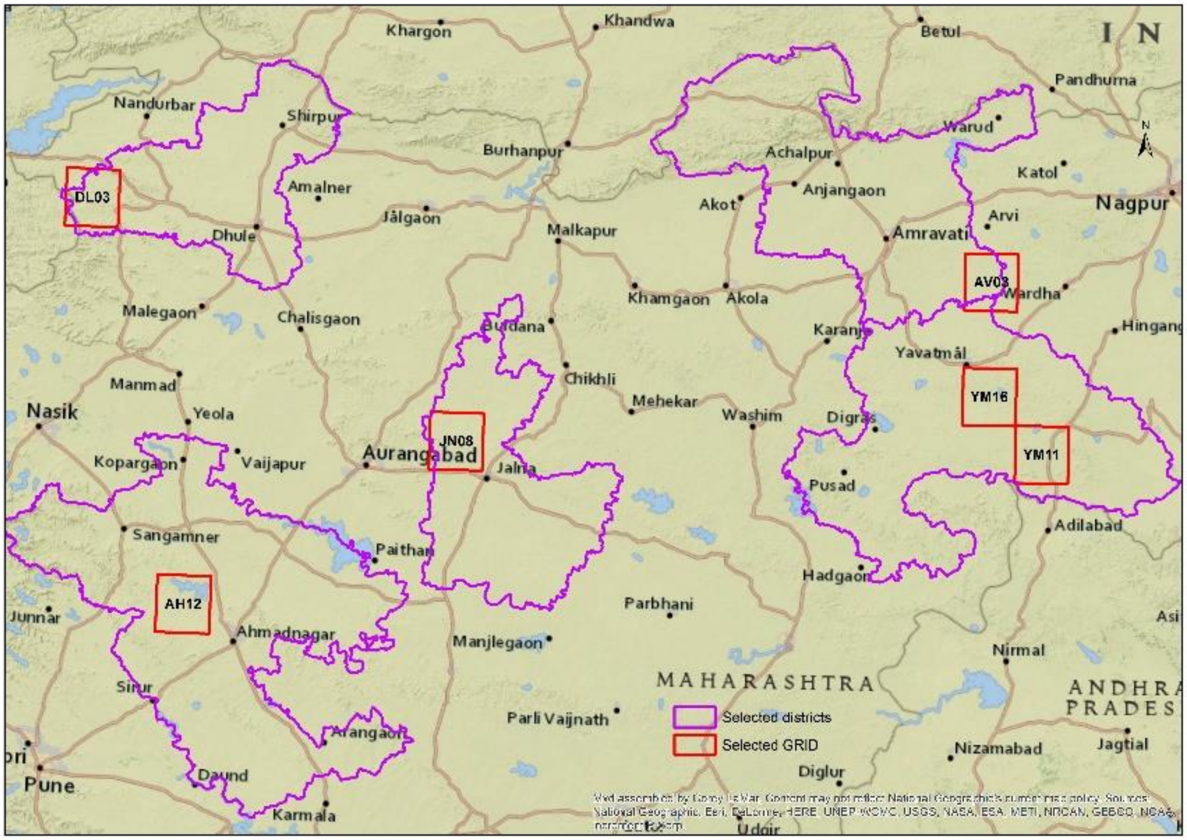


Results

The results section gives you an overview of the impact of various soil fertility management practices in Maharashtra promoted by the soils project. Yield and other selected ecosystem services data were calculated for the five representative grids each one in Ahmednagar (Grid-AH12), in Amaravati (Grid-AV03), Dhule (grid-DL03), Jalna (grid- JN08) and Yavatmal (grid-YM11) (Figure 7).

We present the results here in each detract wise highlighting the impact of soil fertility management practices(IP) on the major cropping systems compared to current existing farmer practices (FP) in terms of yields, nitrogen leaching, soil moisture status and total organic carbon in the soil. We also up-scaled the results and mapped the impact of soil fertility management practices(IP) on the major cropping systems compared to current existing farmer practices (FP) in terms nitrogen leaching, net water storage, total ESS and total profit in all the five study districts. Further we also compared the impact of these soil fertility management practices under two future climate scenarios i.e. cool-wet and hot dry scenarios for the mid-century period. The final maps developed were enclosed in the Appendices 9 to 24.

Figure 7: Location of example grids in the project area



Dhule district grid - DL03

In Dhule the mean annual rainfall is 661 mm and 89% of which will be received during south west monsoon period. On an average during the monsoon 10 days of dry spell is quite common. The major cropping system studied under the current project are cotton, maize as sole crops , soybean-chickpea, soybean-wheat and rice-chickpea as cropping systems.

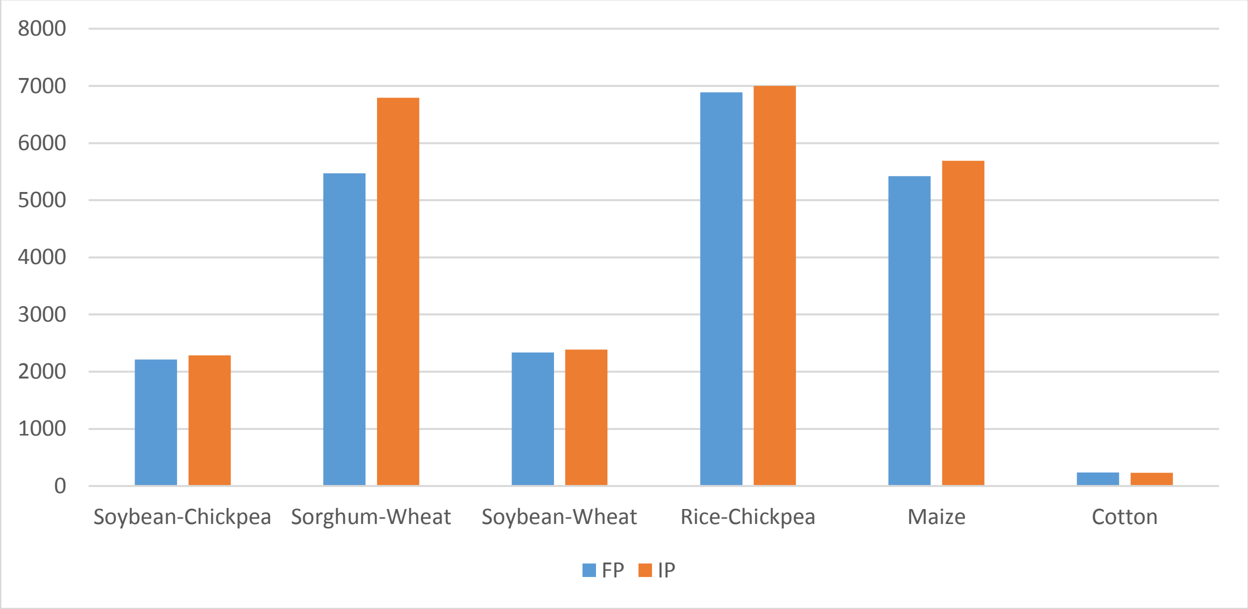
Table 7: Average weather parameters of the Dhule (grid-DL03) study area region

Weather parameter	Normal
Temperature maximum (°C)	34.33
Temperature Minimum	20.16
Total Rainfall (mm)	661
Monsoon RF (mm)	587
Rainy days	46.24
Average continuous dry days during monsoon period	11.7
Average continuous wet days during monsoon period	17.8

Table 8. Cropping system and soil type in Dhule (grid- DL03) study area region

Cropping system	major soil type
Soybean-Chickpea	slightly deep Vertisols
Sorghum-Wheat	slightly deep Vertisols
Soybean-Wheat	slightly deep Vertisols
Rice-Chickpea	Slightly deep Entisols
Maize	Shallow Inceptisols
Cotton	Shallow Inceptisols

Figure 8: Response of various crop and cropping systems to integrated practices (for cropping systems yields are presented as a rainy season crop yield equivalents)



In Dhule among the single crop maize responded well to the integrated packages , adoption of integrated packages in maize resulted in 5.0% increase compared to farmers practices while it was only 3.4% in cotton. Among the cropping systems followed sorghum -wheat and soybean – chickpea responded very positively for IP, however the reposes were quite high with regards to sorghum-wheat cropping stem. It was observed from the survey data that farmers are not applying required N fertilizers for rabi wheat and response to N fertilizer was positive.

Table 9. Ecosystem service parameters as influenced by integrated practices; Yellow- No change (±5%) ; Green: positive ; Red : negative

Cropping system	Yield	Nitrogen Leaching	Extractable Soil Water	Total Organic Carbon	Evapotranspiration
Soybean-Chickpea	🟩	🟨	🟨	🟩	🟨
Sorghum-Wheat	🟩	🟥	🟨	🟩	🟨
Soybean-Wheat	🟨	🟨	🟨	🟩	🟨
Rice-Chickpea	🟨	🟥	🟩	🟩	🟨
Maize	🟩	🟥	🟨	🟩	🟨
Cotton	🟨	🟩	🟨	🟩	🟨

Again for all the crop and cropping systems the integrated management scenario has a positive effect on carbon storage in soils. Even though in both IP and FP there was a net reduction in TOC over 30 bears, but the reduction less in IP compared to FP. Other important ecosystem parameter

Figure 9: Long term data on various ecosystems parameters response to integrated practices in cotton

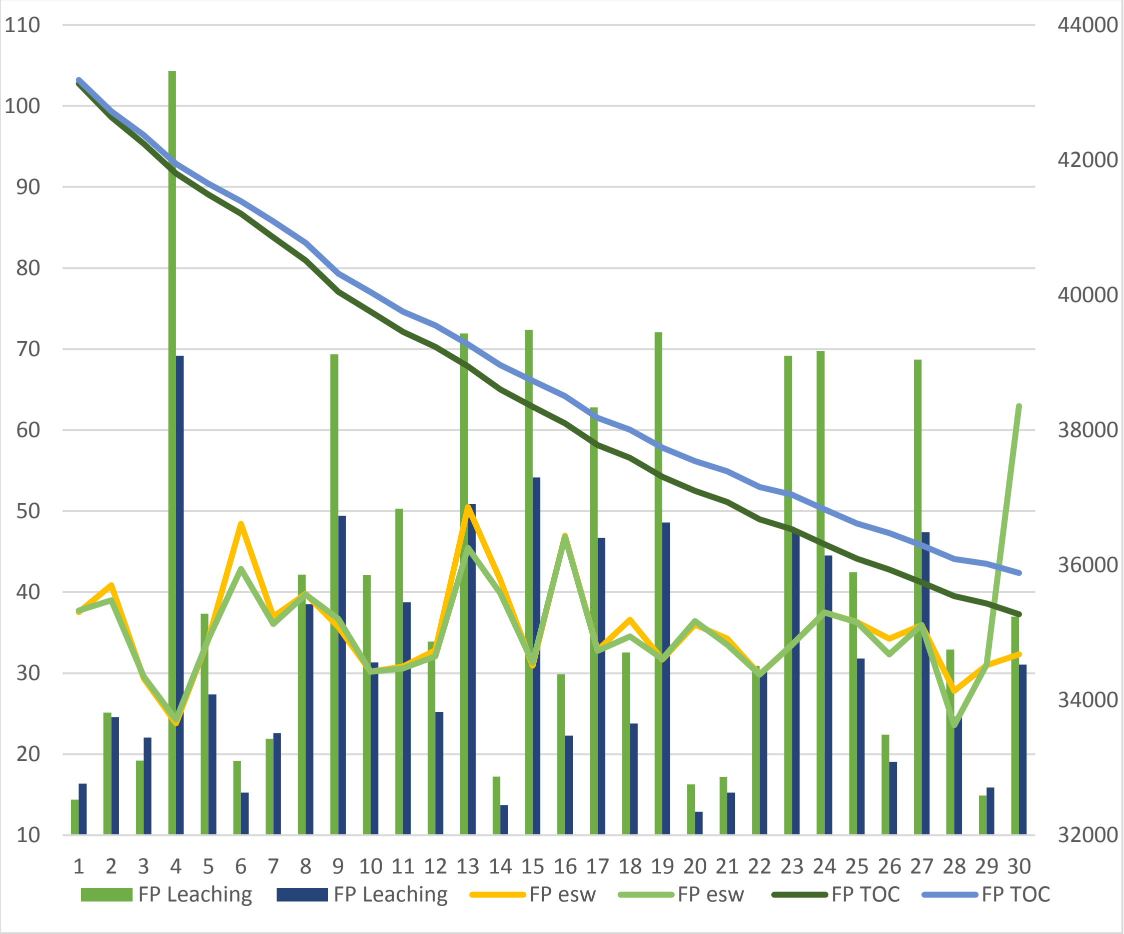
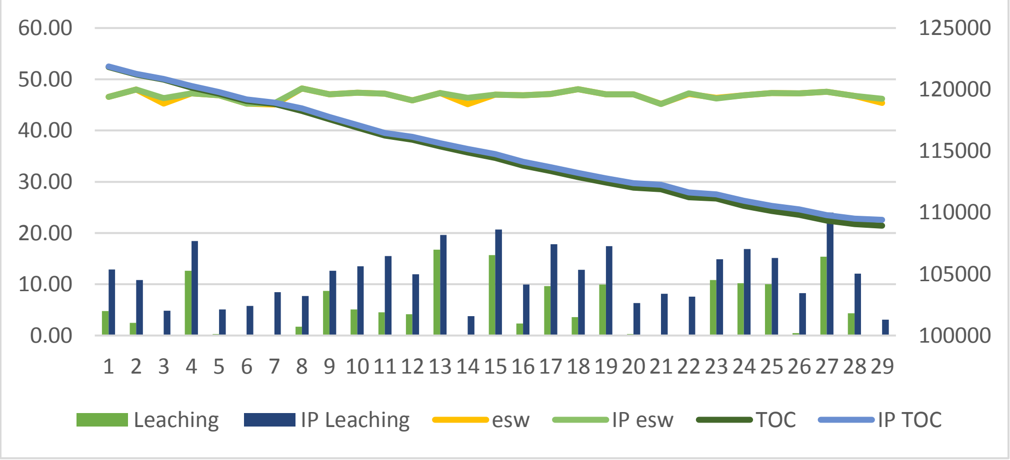


Figure 10: Long term data on various ecosystems parameters response to integrated practices in Soybean-chickpea system



nitrogen leaching was also found to be high in IP for sorghum-wheat, rice-chickpea and maize. The reasons can be attributed to low N application rates in farmer's practices compared to recommend which results in higher yields but also some additional nitrogen leaching amounts. However the overall leaching amounts are considerable low in both systems (Table 9).

Amravathi district

In Amaravati the mean annual rainfall is 1118 mm highest among the study district and 73% of which will be received during south west monsoon period. On an average during the monsoon one week of dry spell is quite common. The number of rainy days also the highest (57) among the study locations (Table 10). The major cropping system studied under the current project are cotton, pigeon pea and soybean as sole crops, soybean-chickpea, and sorghum-wheat as cropping systems (Table 11).

Table 10: Average weather parameters of the Amravati (grid-AV03) study area region

Weather parameter	Normal
Temperature maximum (oC)	33.74
Temperature Minimum	20.86
Total Rainfall (mm)	1118
Monsoon RF (mm)	816
Rainy days	57.18
Average continuous dry days during monsoon period	11.09
Average continuous wet days during monsoon period	19.7

Table 11: Cropping system and soil type in Amravati (grid-AV03) study area region

Cropping system	major soil type
Soybean-Chickpea	slightly deep Vertisols
Sorghum-Wheat	slightly deep Vertisols
Soybean-Wheat	slightly deep Vertisols
Pigeon pea	very deep Vertisols
Soybean-fallow	very deep Vertisols

Figure 11. Response of various crop and cropping systems to integrated practices (for cropping systems yields are presented as a rainy season crop yield equivalents)

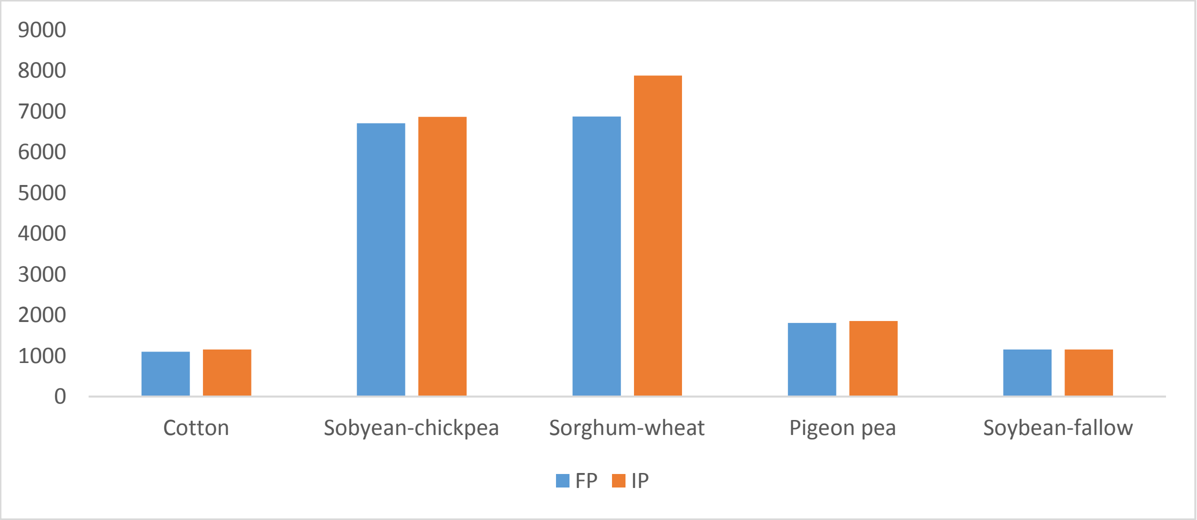


Table 12. Ecosystem service parameters as influenced by integrated practices
Yellow- No change (±5%) ; Green: positive ; Red : negative

Cropping system	Yield	Leaching	Extractable Soil Water	Total Organic Carbon	Evapotranspiration
Cotton	🟨	🟨	🟨	🟩	🟨
Soybean-chickpea	🟨	🟨	🟨	🟩	🟨
Sorghum-wheat	🟩	🟨	🟥	🟩	🟨
Pigeon pea	🟨	🟩	🟨	🟩	🟨
Soybean-fallow	🟨	🟥	🟨	🟩	🟨

In Amaravati among the single crops not much repose was observed in maize, soybean and cotton, however as farmers are applying more fertilizer in pigeon pea (112 kg N/ha) this study shows that recommended N application will be sufficient which not only maintains the yield but also reduces fertilizer cost and nitrogen leaching. Among the cropping systems followed sorghum -wheat responded very positively for IP, however the reposes were quite high with regards to sorghum-wheat cropping stem. It was observed from the survey data that farmers are not applying required N fertilizers for Rabi wheat and response to N fertilizer was positive.

For all the crop and cropping systems the integrated management scenario has a positive effect on carbon storage in soils. In both systems there was a net reduction in TOC over 30 bears, but the reduction less in IP compared to FP. Other important ecosystem parameter nitrogen leaching was also found to be high in IP for soybean fallow and very positive for pigeon. The reasons can be attributed to low N application rates in farmer's practices compared to recommend in soybean and it is vice versa in pigeon pea.

Figure 12: Long term data on various ecosystems parameters response to integrated practices in cotton

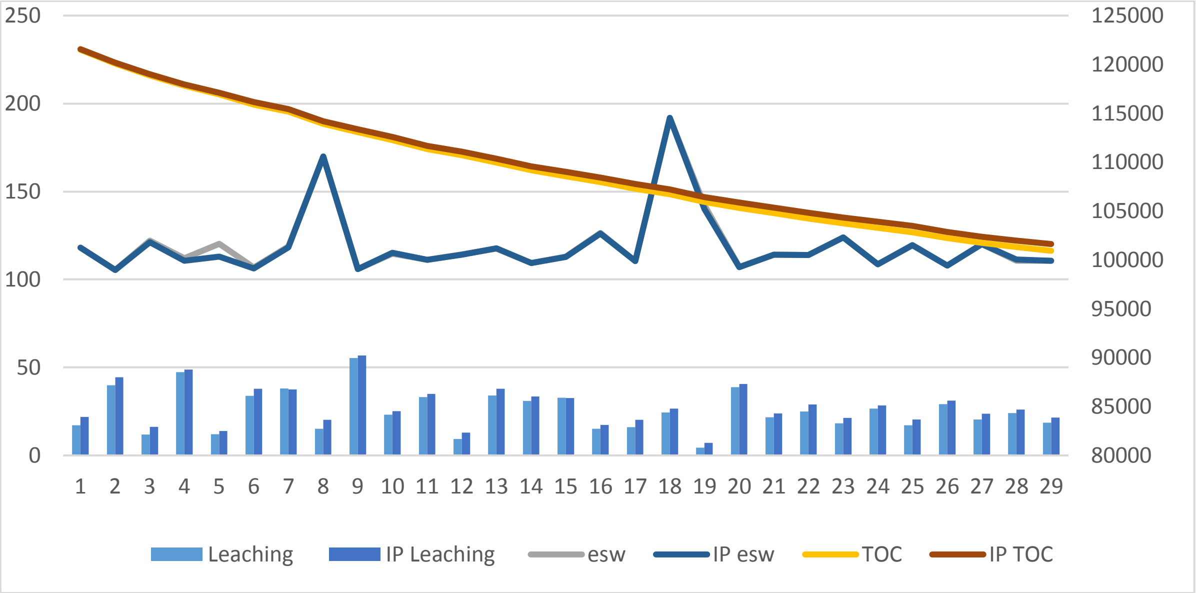
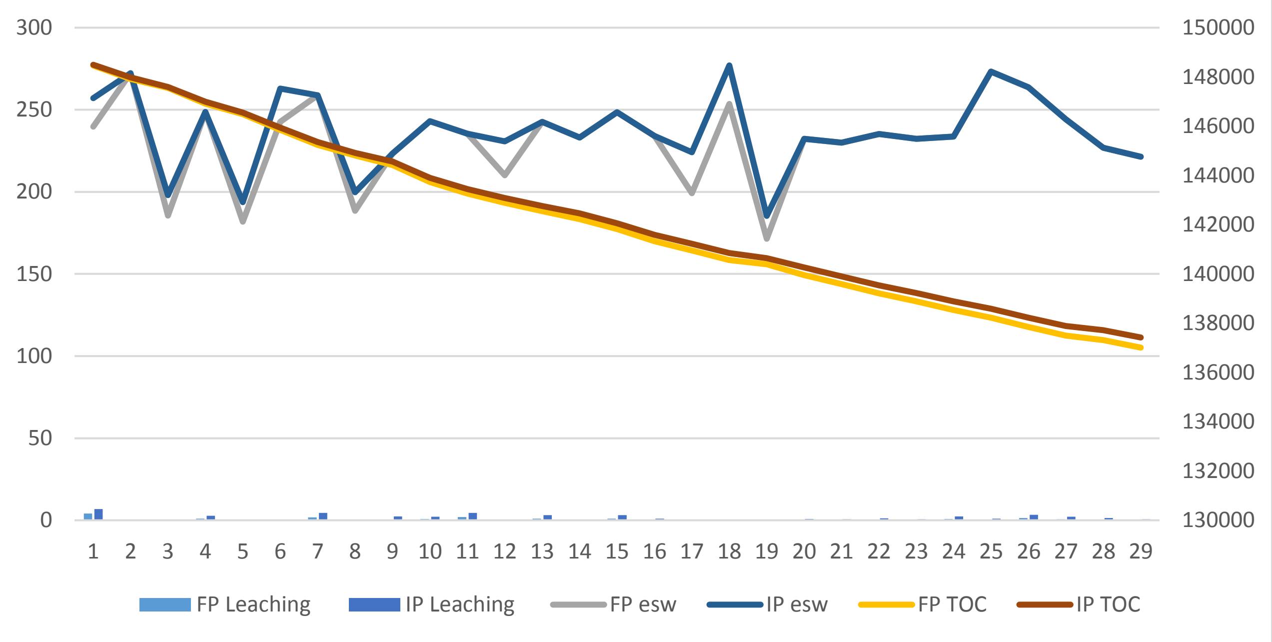


Figure 13: Long term data on various ecosystems parameters response to integrated practices in soybean-chickpea system



Yavatmal district

In Yavatmal the mean annual rainfall is 1002 mm and 88% of which will be received during south west monsoon period. On an average during the monsoon 10 days of dry spell is quite common. The major cropping system studied under the current project are cotton, pigeon pea and sorghum as sole crops, soybean-chickpea and sorghum-wheat as cropping systems.

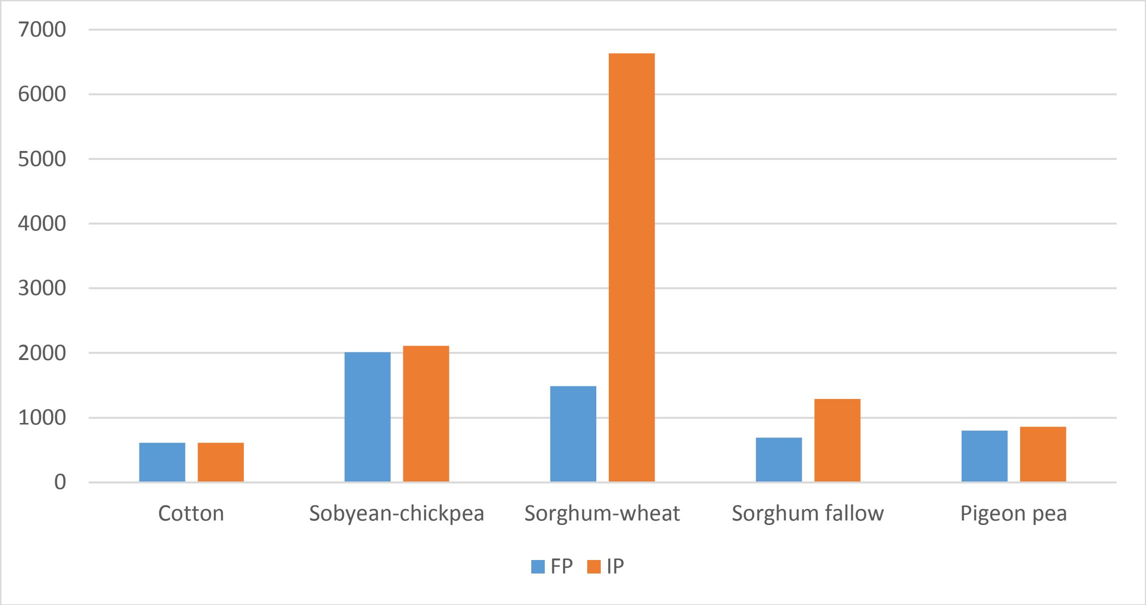
Table 13: Average weather parameters of the Yavatmal (grid-) study area region

Weather parameter	Normal
Temperature maximum (°C)	34.24
Temperature Minimum	21.6
Total Rainfall (mm)	1002
Monsoon RF (mm)	881
Rainy days	59.75
Average continuous dry days during monsoon period	10.31
Average continuous wet days during monsoon period	17.59

Table 14: Cropping system and soil type in Yavatmal (grid- YM11) study area region

Cropping system	major soil type
Cotton	slightly deep Vertisols
Soybean-chickpea	shallow Inceptisols
Sorghum-wheat	very shallow Inceptisols
Sorghum fallow	very shallow Inceptisols
Pigeon pea	very shallow Inceptisols

Figure14: Response of various crop and cropping systems to integrated practices (for cropping systems yields are presented as a rainy season crop yield equivalents)



In Yavatmal among the single crop sorghum responded positively to the integrated packages , adoption of integrated packages in sorghum resulted in 81% increase compared to farmers practices while it was only 1.5% for pigeon pea. Among the cropping systems followed sorghum -wheat responded very positively for IP. It was observed from the survey data that farmers are not applying required N fertilizers for rabi wheat and response to N fertilizer was positive which resulted increase in overall system yields.

Table 15: Ecosystem service parameters as influenced by integrated practices
Yellow- No change (±5%) ; Green: positive ; Red : negative

Cropping system	Yield	Leaching	Extractable Soil Water	Total Organic Carbon	Evapotranspiration
Cotton	🟨	🟨	🟨	🟩	🟨
Soybean-chickpea	🟨	🟥	🟨	🟩	🟨
Sorghum-wheat	🟩	🟨	🟥	🟩	🟩
Sorghum fallow	🟩	🟥	🟨	🟩	🟨
Pigeon pea	🟨	🟩	🟨	🟩	🟨

Again for all the crop and cropping systems the integrated management scenario has a positive effect on carbon storage in soils. Even though in both IP and FP there was a net reduction in TOC over 30 bears, but the reduction less in IP compared to FP. Other important ecosystem parameter nitrogen leaching was also found to be high in IP for soybean-chickpea and sorghum fallow systems. The reasons can be attributed to low N application rates in farmer's practices compared to recommend which results in higher yields but also some additional nitrogen leaching amounts. However

Figure 15: Long term data on various ecosystems parameters response to integrated practices in cotton

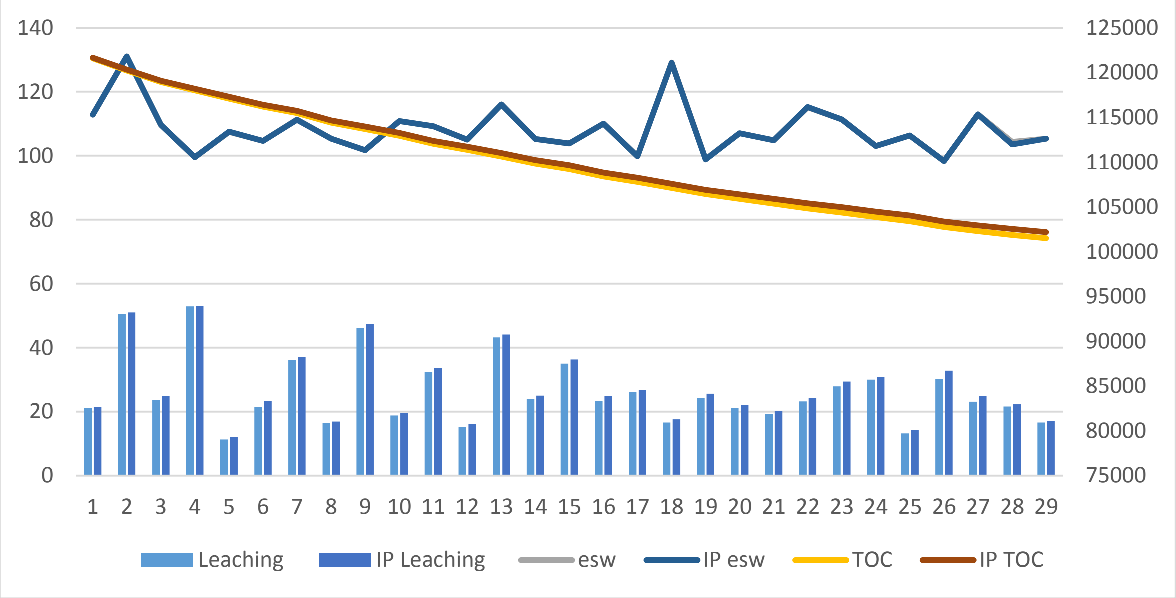
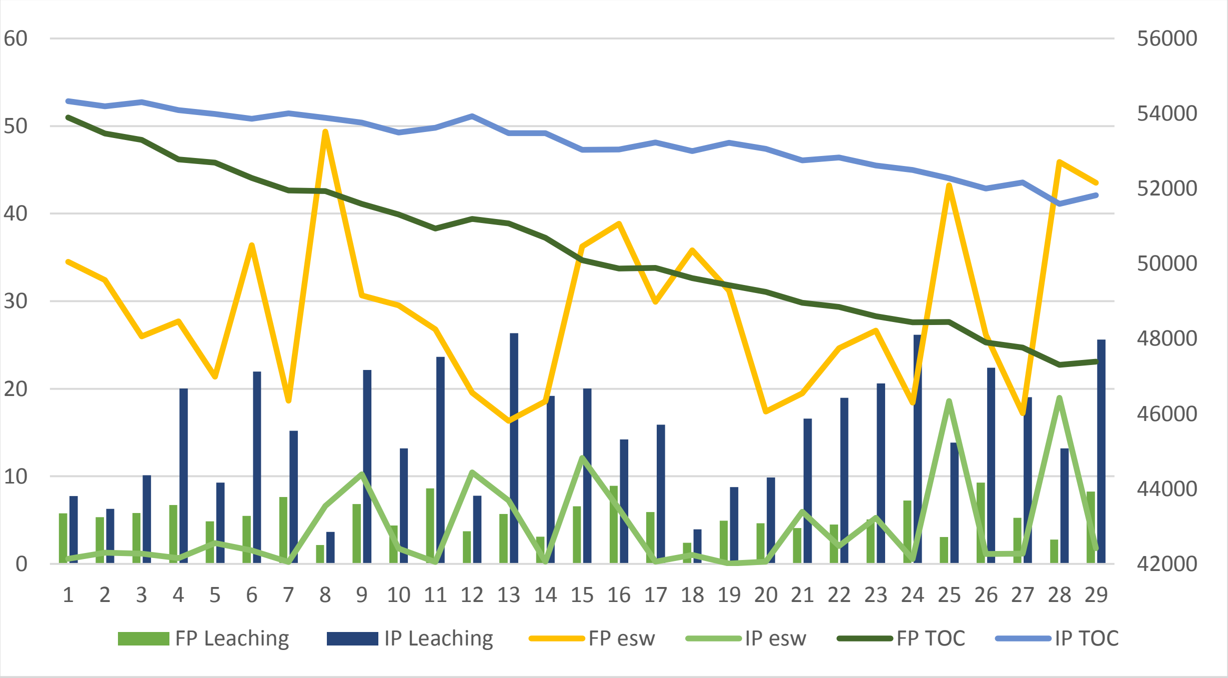


Figure 16. Long term data on various ecosystems parameters response to integrated practices in sorghum-wheat system



the overall leaching amounts are considerable low in both systems. Among the cropping systems integrated package in sorghum- wheat resulted in overall system yields but it also extracted more water from the soil profile.

Jalna district grid-JN08

In Jalna the mean annual rainfall is 771 mm in the study district and 85% of which will be received during south west monsoon period. On an average during the monsoon 10 days of dry spell is quite common. The average number of rainy days were 52 during monsoon period. The major cropping system studied under the current project are cotton and maize as sole crops, soybean-wheat and sorghum-wheat as cropping systems.

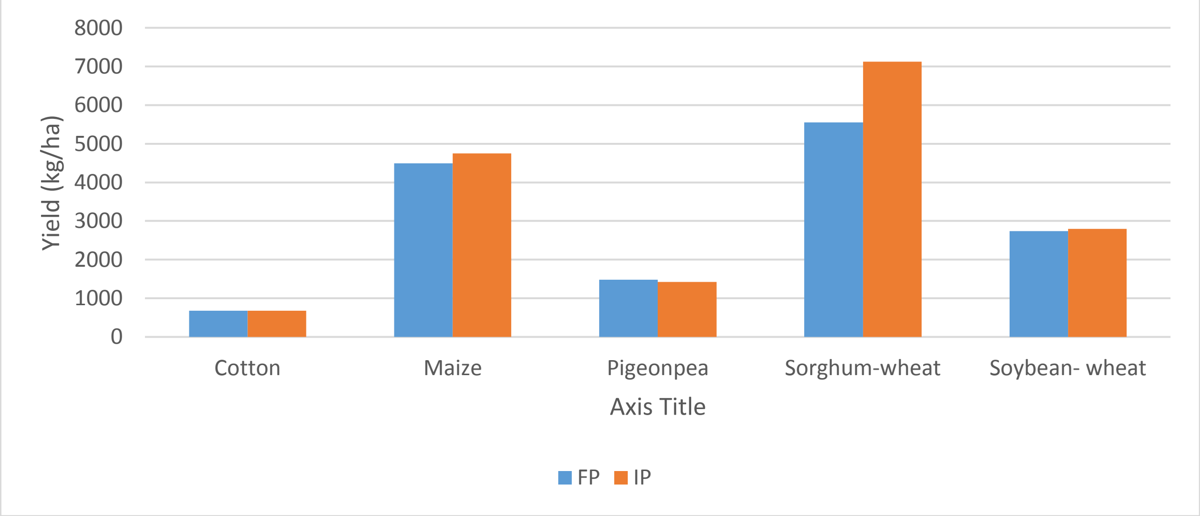
Table 16: Average weather parameters of the Jalna (grid-JN08) study area region

Weather parameter	Normal
Temperature maximum (oC)	33.83
Temperature Minimum	20.37
Total Rainfall (mm)	771
Monsoon RF (mm)	652
Rainy days	52
Average continuous dry days during monsoon period	10.36
Average continuous wet days during monsoon period	14.95

Table 17: Cropping system and soil type in Jalna (grid-JN08) study area region

Cropping system	major soil type
Cotton	slightly deep Vertisols
Maize	Very shallow Entisols
Pigeon pea	Very shallow Entisols
Sorghum-wheat	slightly deep Vertisols
Soybean- wheat	slightly deep Vertisols

Figure 17: Response of various crop and cropping systems to integrated practices (for cropping systems yields are presented as a rainy season crop yield equivalents)



In Jalna among the single crops not much repose was observed in maize and cotton, however as farmers are applying more fertilizer in cotton this study shows that recommended N application will be sufficient which not only maintains the yield but also reduces fertilizer cost and nitrogen leaching. Among the cropping systems followed sorghum -wheat responded very positively for IP. In the sorghum –wheat system the response of wheat for recommended fertilizer application was very positive. The rainy season sorghum also responded positively for one strategic irrigation from the water collected from farm ponds

Table 18: Ecosystem service parameters as influenced by integrated practices; Yellow- No change (±5%); Green: positive; Red: negative

Cropping system	Yield	Leaching	Extractable Soil Water	Total Organic Carbon	Evapotranspiration
Cotton	🟨	🟩	🟨	🟩	🟨
Maize	🟨	🟨	🟨	🟩	🟨
Pigeon pea	🟨	🟩	🟨	🟩	🟩
Sorghum-wheat	🟩	🟨	🟨	🟨	🟨
Soybean- wheat	🟨	🟩	🟨	🟩	🟨

Again for all the crop and cropping systems the integrated management scenario has a positive effect on carbon storage in soils. Even though in both IP and FP there was a net reduction in TOC over 30 bears, but the reduction less in IP compared to FP. Other important ecosystem parameter nitrogen leaching was also found to be very positively (less N leaching) responded for IP in almost all the systems. The IP showed more positives in this district in terms of ESS parameters.

Figure 18: Long term data on various ecosystems parameters response to integrated practices in cotton

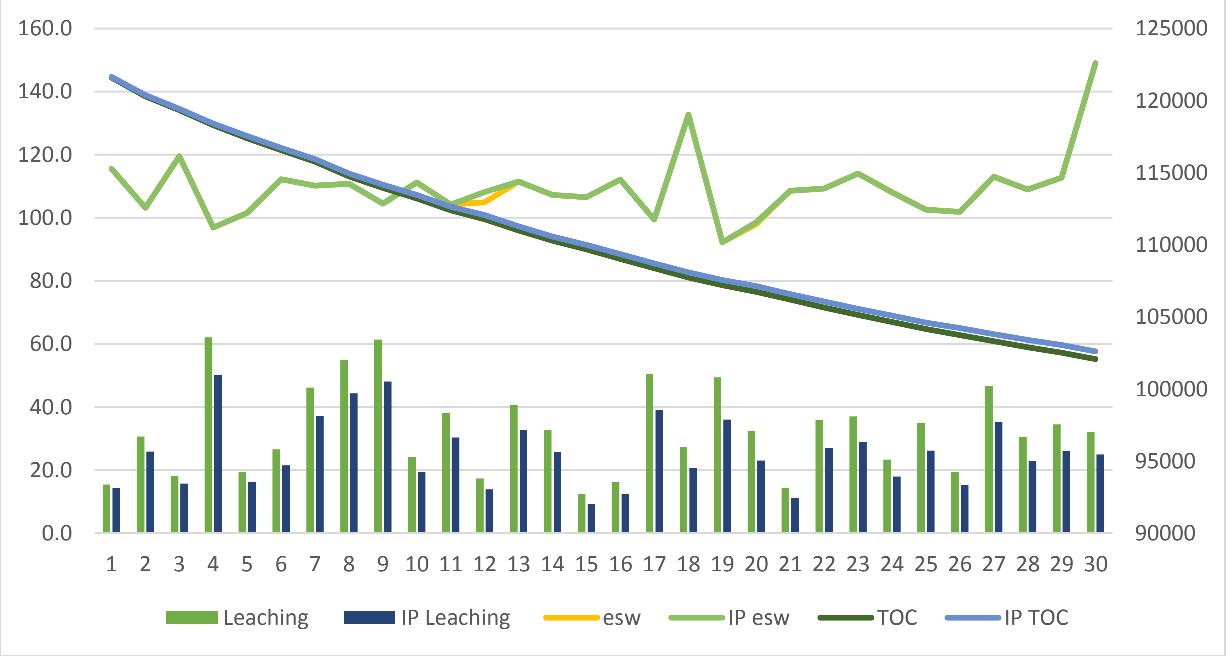
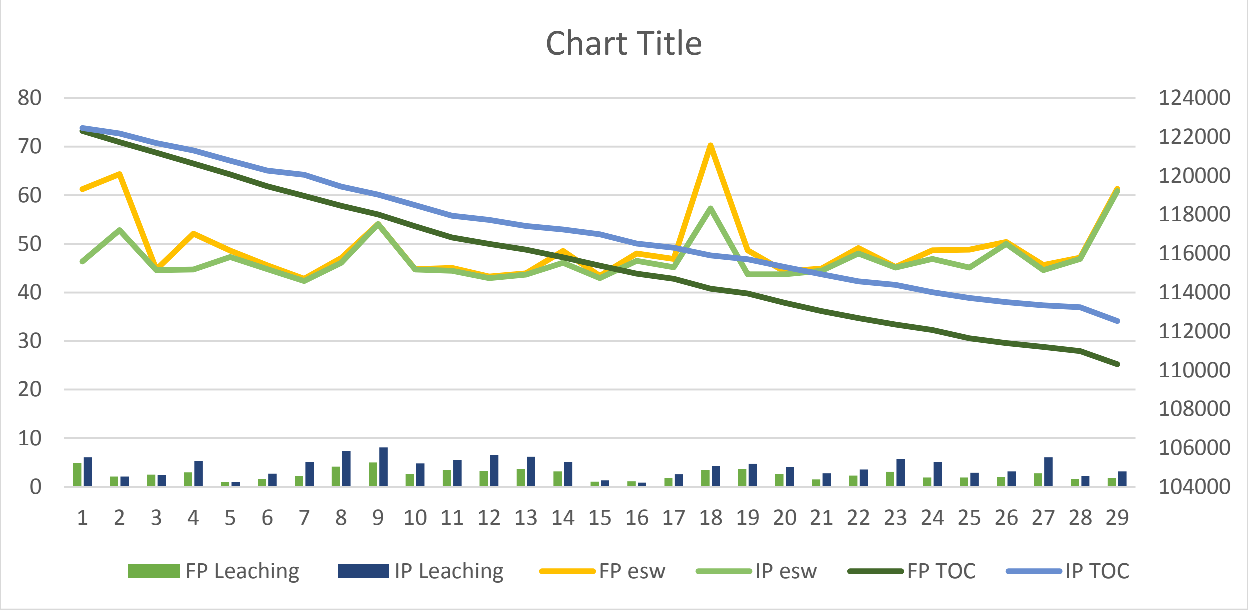


Figure19: Long term data on various ecosystems parameters response to integrated practices in sorghum- wheat system



Ahmednagar district grid-AH12

In Jalna the mean annual rainfall is 596 mm least among the study districts and 80% of which will be received during south west monsoon period. On an average during the monsoon two weeks of dry spell is quite common. The average number of rainy days were 41 during monsoon period. The major cropping system studied under the current project are cotton , rabi sorghum, millet, soybean and pigeon pea and maize as sole crops, green gram-sorghum and maize-chickpea as cropping systems .

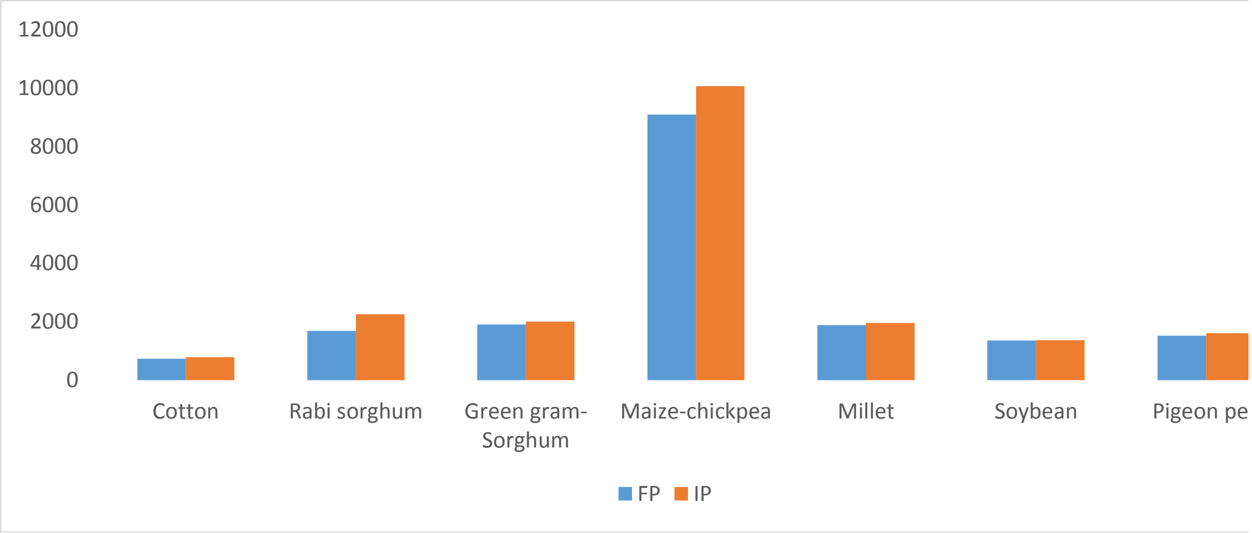
Table 19: Average weather parameters of Ahmednagar (Grid-AH12) study area

Weather parameter	Normal
Temperature maximum (°C)	33.19
Temperature Minimum	19.43
Total Rainfall (mm)	596
Monsoon RF (mm)	472
Rainy days	41.25
Average continuous dry days during monsoon period	12.76
Average continuous wet days during monsoon period	12.13

Table 20: Cropping system and soil type in study area region

Cropping system	major soil type
Cotton	Slightly deep Inceptisols
Rabi sorghum	Deep Entisols
Green gram-Sorghum	Deep Entisols
Maize-chickpea	Deep Entisols
Millet	Deep Entisols
Soybean	Slightly deep Inceptisols
Pigeon pea	Deep Entisols

Figure 20: Response of various crop and cropping systems to integrated practices (for cropping systems yields are presented as a rainy season crop yield equivalents)



In Ahmednagar all the crops and cropping systems responded positively as the rainfall is very less, possibility of two weeks of dry spell, the integrated package which included one strategic irrigation using farm pond collected water resulted in positive increments in yields. Among the single crops pigeon pea, rabi sorghum showed positive responses compared to other, however as farmers are applying more fertilizer in cotton this study shows that recommended N application will be sufficient which not only maintains the yield but also reduces fertilizer cost and nitrogen leaching. Among the cropping systems green garm –sorghum and maize chickpea responded positively with an average increase of yields 10.4 & 8.8% respectively.

Table 21: Ecosystem service parameters as influenced by integrated practices Yellow- No change (±5%); Green: positive; Red: negative

Cropping system	Yield	Leaching	Extractable Soil Water	Total Organic Carbon	Evapo-transpiration
Cotton	🟨	🟩	🟨	🟩	🟨
Rabi sorghum	🟩	🟩	🟩	🟩	🟨
Green gram-Sorghum	🟩	🟨	🟥	🟩	🟨
Maize-chickpea	🟩	🟥	🟨	🟩	🟨
Millet	🟩	🟥	🟨	🟩	🟨
Soybean	🟨	🟥	🟨	🟩	🟨
Pigeon pea	🟩	🟥	🟨	🟩	🟨

Again in this district also for all the crop and cropping systems the integrated management scenario has a positive effect on carbon storage in soils. Even though in both IP and FP there was a net reduction in TOC over 30 bears, but the reduction less in IP compared to FP. Other important ecosystem parameter nitrogen leaching was also found to be high in IP for maize-chickpea, soybean and millet. The reasons can be attributed to low N application rates in farmer's practices compared to recommend which results in higher yields but also some additional nitrogen leaching amounts. However the overall leaching amounts are considerable low in both systems.

Figure 21: Long term data on various ecosystems parameters response to integrated practices in cotton

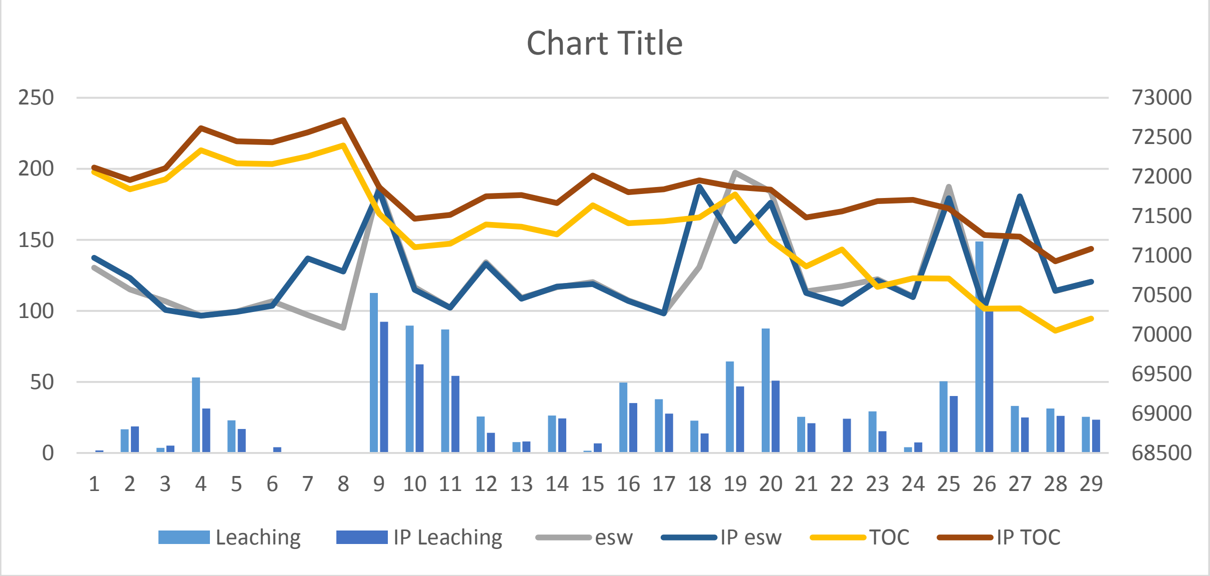
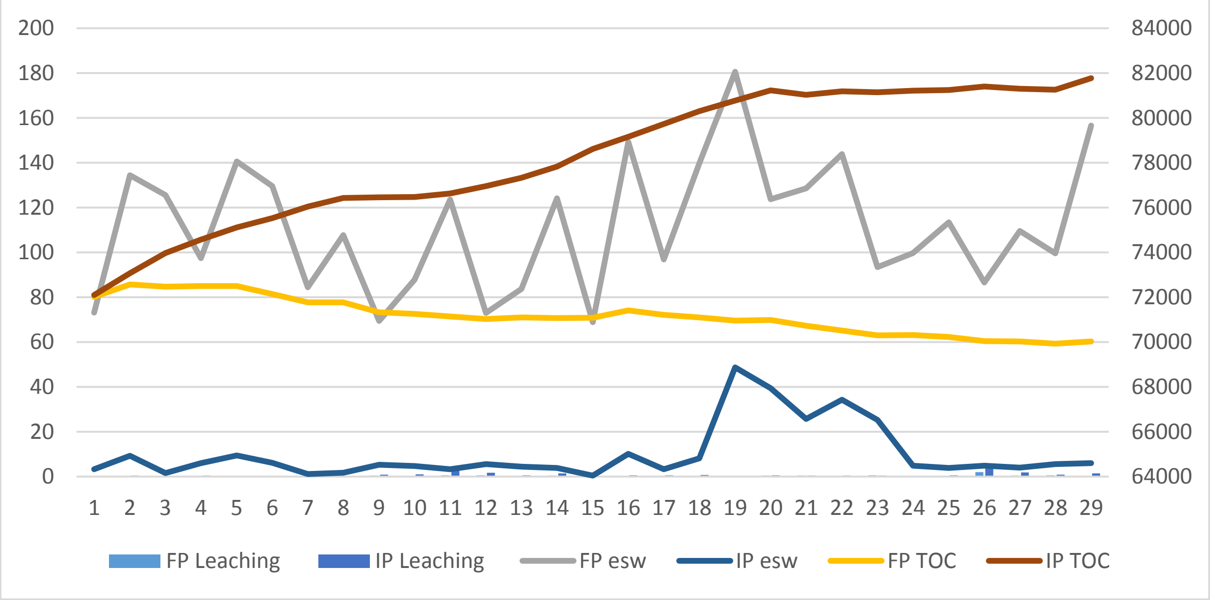


Figure 22: Long term data on various ecosystems parameters response to integrated practices in green gram-sorghum system



Spatial analysis of impact of various sustainable land management practices on ecosystem services in Maharashtra

Global studies on linking crop models with a Geographical Information System (GIS) have demonstrated the strong feasibility of crop modeling applications at a spatial scale. Most agricultural operations closely connected with natural resources that vary spatially. Spatial data analyses is well complementing environmental and agricultural modeling. Several researchers have successfully used crop models and GIS to study spatial water requirement of crops, yield forecasting and climate change impacts at watershed and regional scales. In this present analysis we combined remote sensing, GIS and simulation modeling tools as shown in Figure 5.

Nitrogen leaching

Appendices 9 & 10 depict nitrogen leaching under farmers and improved practices. The regions where strongest N leaching occur generally correspond with regions of highest N application rates. Highest N leaching rates occur in cotton growing regions in Ahmednagar and Jalna. Nevertheless, restricting N application rates to recommended practices has reduced the N leaching considerably in these regions (Appendix 10). Soybean – maize growing regions also showed considerable N leaching. The spatial patterns in Figure 9 are largely mirrored by total N application rates of the system indicating that with higher N inputs the relative importance of leaching increases.

Net water storage

Appendices 11 & 12 show net water storage under farmers and improved practices. Not much differences were observed between both practices. However the net water storage was largely depended on soil type with fine textured soils showing more moisture than coarse textured soils.

Total organic carbon

Appendices 25 & 26 depict long term total organic carbon buildup in various cropping systems across study locations. The long-term simulation data, starting from 1980 -2009 indicated more clear decreasing trends of TOC concentration in most of the cropping systems. Recommended practices showed slight buildup of TOC especially in pulse based systems. TOC build up was observed under recommended practices in soybean based system in Jalna, sorghum-chickpea system in Thule and pigeonpea in Ahmednagar.

Discussion

In the current study we estimated the impact of cropping system and soil fertility management practices on selected ecosystem services in the context of semi-arid areas. The main ecosystem parameters we targeted in this study are nitrogen leaching from crop fields, extractable soil water at harvest, total organic carbon, evapotranspiration from crops. We conducted this study in five districts in Maharashtra having various rainfall and temperature patterns. We used APSIM model to simulate crop yields and various ESS parameters. Using remote sensing based crop type map we identified the major crop grown in the district and accordingly using NBSSLUP soil map we identified major soil in which a particular crop was grown. In the study we found considerable variability in the value estimates depending upon the region, soil type and crops grown for the improved practices. In the high rainfall regions (Amravati and Yavatmal) in the selected grids we observed not much improvements in the ESS parameters for the crop studied irrespective of the soil types, however due to adoption of IP wherever the responses in terms of total biomass is higher which in turn results in high root and shoot biomass, resulted in high TOC in soil (20% of the total biomass in incorporated in the soil). Among different soil types shallow and extremely shallow soils the integrated packages results in buildup of TOC but on the other hand it has a negative impact on nitrogen leaching.

In general the ecosystem processes depend on landscape configuration, climate factors, and crops grown. These processes affect ecological indicators like net primary productivity, runoff, nutrient cycling, which in turn effects most of ecosystem services (Alberti, 2005). One main concerns this research raises Perhaps is how ecosystem service values should be used in policy and decision making. Ecosystem service valuation in particular has had little role especially in agriculture in India. The current study can be a valuable tool in assessing the non-market return on investment from improved management practices in addition to routine yield and economics estimates.

Evaluating the impact of agricultural practices on ecosystem service provision

Sonja Limberger

Agriculture is the most widespread land management system worldwide. According to estimations of the FAO, around 40% of terrestrial surface is covered by agricultural ecosystems. If managed appropriately and with sustainable practices agriculture is a provider of a great diversity of ecosystem services such as food, pollination, pest control, soil conservation, water provision, carbon sequestration and many more (Power 2010). Nevertheless, many management practices cause the loss of biodiversity and habitat for wildlife, nutrient loss, runoff, sedimentation of waterways, or release of greenhouse gas emissions, which are examples for ecosystem disservices (Zhang et al. 2007). Often there are trade-offs with regard to the impact of agricultural practices on different ecosystem services. Sustainable land management practices such as extensive tillage, integrated fertilizer application or crop rotation systems are in tendency supporting the provision of regulating services while intensive agriculture maximizes rather provisioning ones. There are exceptional examples when both can be optimized simultaneously (Power 2010). In many situations, management options are preferred which maximize provisioning services such as yield, fiber or bioenergy. They are typically private goods for which markets exist. There are strong incentives for farmers to concentrate on such tradeable goods. Regulating ecosystems are often public goods and regularly neglected in decision making (Swinton et al. 2007).

The diverse nature of ecosystem services makes it difficult to make well informed decisions which are in the interest of the overall society. Estimating monetary values can support policy and decision makers in assessing trade-offs that arise from different agricultural practices. It is a widely recognized approach to search for prices of ESS that lack market values (Zhang et al. 2007).

The broad range of studies supports the importance of ESS evaluation (Zhang et al. 2007). (Ninan and Inoue 2013) give a detailed overview of studies in different contexts. Monetary evaluation studies are guided by specific management challenges. One widespread application is to make decisions about fundamental land use transformations. Several papers focus on the evaluation of ESS on a global scale (e.g. Pimentel et al. 1997; Costanza et al. 1997; Patterson 2002). A number of studies assess ESS on forest ecosystems (e.g. Guo et al. 2001; Xue and Tisdell 2001; Ninan and Kontoleon 2016). Another line of research evaluated watershed protection and hydrological services (e.g. Badola et al. 2010; Xie et al. 2010). Important in the context of our study is the work on soil conservation (e.g. Wei et al. 2010; Xie et al. 2010; Ninan and Inoue 2013) and carbon sequestration (e.g. van Beukering, Cesar, and Janssen 2003; Croitoru 2007; Badola et al. 2010). The methods chosen vary between the contexts. Bateman et al. (2011) and DEVRA (2007) provide overviews on the diversity of ESS assessment and evaluation methodologies.

Our study focuses on the evaluation of ecosystem services influenced by farmer's agricultural practices and soil management in the central Indian context. This is a field in which so far only few studies have been conducted (e.g. Johnson, Adams, and Perry 1991; Kragt and Robertson 2014). The motivation of the research is to help policy makers and farmers to identify ecosystem service smart agricultural technologies and practices (Tilman et al. 2002; Wani et al. 2003). The study assesses the economic impacts of various sustainable soil management approaches with the intention to eventually provide arguments for farmers, policy makers and other critical actors to promote soil protection and rehabilitation of degraded soils.

Despite the advantages that the evaluation of ESS promotes, there are also some limitations that must be considered. The reviews of several ESS studies reveal great challenges related to uncertainties. As an example serves the study of Costanza et al. (1997), that ventured on the value estimation of global ecosystems services and natural capital. Here the economic value ranges between 16 - 54 trillion US$ per year (Costanza et al. 1997. Results of an evaluation depend therefore strongly on the scope of the analysis. The broader the scope, the greater uncertainties become.

Further, the choice of valuation method determines the outcome. There is a broad set of valuation methods; all of them face specific limitations. The most common method which is the market price method is e.g. limited to those ecosystem services for which a market exists. Cost-based approaches, however, can easily overestimate the actual value (DEVRA 2007). The replacement cost approach assumes a substitution between a market good and a natural resource. Often such substitutes do not exist or do not provide the exact same kind of benefit as the natural resource. In addition, when evaluating ESS separately, double-counting of values has to be carefully avoided. Double counting is critical especially for regulating ESS because benefits from ecological processes of various ESS often overlap. Therefor it is advisable to evaluate only final services (DEVRA 2007). Those are only some of the challenges that have to be taken into account when identifying the best suited valuation method for a specific context (King and Mazzotta 2000).

In a next step we will summarize our evaluations strategy. Generally the analysis of ecosystem services follows a framework that consists of three major parts: Firstly, the measurement of the provisioning, regulating and supporting ecosystem services. Secondly, the determination of the monetary value of those services and thirdly, the design of policy tool in order to manage the ESS accordingly to the results (Polasky 2008). It has been explained in section "Estimating the impact of agricultural practices on ecosystem service provision" how we use crop modeling to quantify ESS impacts. We will now focus on the approaches for determining prices for each considered ESS.

Methodology evaluation

We will ESS by ESS explain our strategy of estimating the monetary value for each of it. Table 22 gives an overview of the studied ecosystem services and disservices, as well as the economic valuation methods used.

Table 22: ESS and evaluation methods

ESS	Service or disservice	Method	Procedure
Yield	Income and source of nutrition	Market price method	Yields are evaluated based on market prices for crops
By-products	Source of nutrition	Market price method	By-products are evaluated based on market prices for fodder
Water consumption	Irrigation water is crucial input factor for agricultural productivity	Opportunity cost method	Evaluation based on market prices for water from water utilities

Moisture storage	Affects agricultural productivity, yield and nutrition	Alternate cost method	Conserved water in soil will be estimated based on water storage costs in a men made reservoir
Nitrogen leached	Disservice; affects water quality, aquatic wildlife, nutrition and health	Replacement cost method	Leaching levels will be evaluated based on total costs of a constructed wetland in order to purify water
Total organic carbon	Carbon storage in soil mitigates climate change	Market price method	Evaluation based on market prices for carbon credits

Yield

The valuation method that is predominantly used in literature to value the provisioning ecosystem service of yield is the direct market price method (Costanza et al. 1997; Chen et al. 2009; Qian and Linfei 2012; Schaubroeck et al. 2016; Toledo et al. 2017). Advantages of this approach are that it reflects individual's willingness to pay for costs and benefits of goods that are bought and sold in markets. Furthermore prices and cost data are relatively easy to obtain for established markets and simple standard economic techniques are applied (King & Mazzotta, 2017). Hence this method was chosen to calculate the economic value of yields from different cropping systems and management practices. The following equation is used to account for the net profit from crop yields:

$$\text{(1)}\quad \textbf{ESS Value of Yield}\ \frac{INR}{ha} = \textbf{Yield}\ \frac{kg}{ha} * \textbf{Crop price}\ \frac{INR}{kg} - \textbf{Production Costs}\ \frac{INR}{ha}$$

main source for crop prices is *AgMarknet*, a sub scheme of the Integrated Scheme for Agricultural Marketing (ISAM) which provides electronic information of the wholesale markets of India (AgMarknet 2017). More than 100.000 crop price data from 2012 to 2017 were collected for the study area. Each crop price from 2012-2015 was adjusted to inflation using corresponding rural CPI rate in order to convert the data to 2016 prices (Reserve Bank of India 2017). Price fluctuations and general differences between the markets and districts were taken into account by conducting an analysis of variance (ANOVA) with alpha=0,05. The results of the ANOVA showed that there are no significant price differences between the districts and the markets for the majority of analyzed crops. Therefore the average price of the last five years over all regions was being used for further calculations. Table 23 lists the calculated prices for the chosen set of crops.

Table 23: Crop prices in INR/kg; Source: Own calculations based on AgMarknet, 2017

	Crop Price
Chickpea	46
Cotton	49,4
Green Gram	57,9
Maize	14,1
Millets	14,9
Paddy	14,7
Pigeon Pea	56,7
Sorghum	17,4
Soyabean	34,1
Wheat	17,1

Production costs (PC) for the different crops were mainly collected from the Commission of Agricultural Costs and Prices (CACP 2017) and the Directorate of Economics and Statistics; both of them use the same database (Directorate of Economics and Statistics 2017). Production costs from both states Madhya

Pradesh and Maharashtra were collected for each crop included in the set for the production year 2013-2014. Production costs were adjusted to inflation using the rural cost price index (CPI) by Reserve Bank of India and converting cost data from 2013-2014 to 2016 prices at conversion factor of 1,12 (100=2016) (Reserve Bank of India 2017). CACP provides information for each cost item included in the production cost. We chose to include all cost items according to the calculation method A1 (Meena, Singh, and Meena 2016). Hence, the cost of cultivation comprises causal human labor, hired animal and machinery labor, costs for seeds, insecticides, and irrigation as well as organic and inorganic fertilizer. Moreover the calculation method accounts for depreciation on equipment and buildings and includes land revenues as well as taxes.

In order to differentiate production costs of the three management scenarios, the costs of fertilizers were calculated based on distinctive fertilizer application patterns for the management scenarios and added to the remaining cost items given by CACP. The first scenario “farmer practices” assumes current farmer’s fertilizer application patterns. The third scenario “integrated practices” suggests in addition to a certain amount of recommended inorganic fertilizer, the application of farm yard manure and irrigation from farm yard ponds which is calculated at 500 INR/ha. The later decisions were made on the basis of the survey conducted by ICRISAT in the frame of this study (see Section “Land Use and Farming System description”).

In addition it had to be considered that the production costs describes among others the costs related to the harvest of the biomass. As not only the main product but also the byproducts are harvested we conduct a proportion claw back of production costs in order to avoid double counting, when evaluating the value of byproducts. Herby we use a percentage rate for each crop.[3] Finally we get a production cost for the main product as well as a production cost for the by-products. Grid specific irrigation patterns were considered and production costs adjusted accordingly.

Finally the calculation of yield values was conducted according to the formula and the depicted prices for the crops and the costs of production with the statistical program R Studio.

By products

By products from agricultural production can have several uses such as fodder, green fertilizer, or provides energy from biofuels. We focused on the use of fodder because this utilization pattern is predominant in the study area. A recent studies from India estimates the value of free grazing values in forests using fodder prices (Ninan and Kontoleon 2016). *AgMarknet* or CACP do not publish official market prices for fodder. We therefore included this question onto our survey and Focus Group discussions (FGDs). Thus, using a similar valuation approach for yield, the market price method is used for valuation. The following equation was developed:

$$\textbf{(2)}\quad \textbf{ESS Value of byproducts}\ \frac{INR}{ha} = \textbf{Byproducts}\ \frac{kg}{ha} * \textbf{Fodder price}\ \frac{INR}{kg} - \textbf{Production Costs}\ \frac{INR}{ha}$$

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[3] The percentage rate is calculated by dividing the value of the main products by the summarized value of main and by-products. To calculate the value of the by-product the value of by-product is divided by the summarized value of main and by-products, respectively. The data values of the main and the by-products were sourced from Directorate of Economics and Statistics for MAH and MP. (Directorate of Economics and Statistics, 2017)

Prices for fodder used in other studies vary around 1,8 INR/kg (Badola et al. 2010; Ninan and Kontoleon 2016). Fodder prices from the FGDs in Maharashtra result between 1,6 INR/kg in Derwadi (Ahmednagar, MAH), 5 INR/kg in Bhagerwadi (Ahmednagar, MAH) and 10 INR/kg in Hiwoukorda (Ahmednagar, MAH). Based on the results of our survey, the FGDs and expert interviews we set the fodder price to 1,8 INR/kg. Cotton byproducts have very low value and are mainly used as subsistence source of fuel. In contrast Sorghum has an exceptional nourishing value. Based on the aforementioned sources we set a lower price of 0,5 INR/kg for cotton and a higher price of 3 INR/kg for Sorghum. Again a proportional calculation of production costs is applied in order to avoid double counting.

Water consumption

The water consumption strongly depends on the agricultural practices. In particular irrigation management and crop choices determine the water demand of a system (Fishman, Devineni, and Raman 2015). Our study approach assesses water consumption of different cropping and management systems.

An initial approach developed for evaluating water consumption, followed the logic that if water can be saved at one plot due to a water efficient cropping system, then this water will be available on another plot to irrigate a fallow field. The additional amount in yields due to this additional irrigation will then be evaluated based on the market price of the grown crop as an estimate for the value of reduced water consumption. The yields depend, however, on a number of management factors and we felt it would have been a very arbitrary choice to set the water price based on the yields of one system. Another upcoming question has been whether to use only the yield income or the overall ecosystem service value. We therefore searched for an alternative approach.

Studies such as Broekx et al. (2013a) and Schaubroeck et al. (2016) use water product prices to estimate the cost of lost freshwater. The local stock of water is determined by runoff, evapotranspiration and infiltration. Both, runoff and evapotranspiration lead to a potential loss of water at the particular locality. We assume that water used at one location can only after a considerable hydrological cycling process be used elsewhere (Keys et al. 2012). In reference to studies such as the ones of Jobbágy and Jackson (2004) and Maes, Heuvelmans, and Muys (2009) we consider evapotranspiration as the amount of water locally lost. Evapotranspiration can be estimated as the precipitation subtracted by water infiltration. Runoff was neglected because there was almost no slope in the study area. We are aware that this is a simplification of the much more complex water cycle (Fürstenau et al. 2007; Ninan and Inoue 2013). Nevertheless, it was beyond the scope of this study to assess the hydrological processes in more detail.

Based on this methodological assessment and taking limitations into account we follow the approach of Broekx et al. (2013) and Schaubroeck et al. (2016) for the valuation of water consumption and apply an opportunity cost approach. We assume that fewer loss of water leads to a potential use somewhere else. A corresponding product price of water was referred from the Ministry of Urban Development, Government of India and the Asian Development Bank who published a data book of water prices of water utilities in India from 2007. The costs for water from utilities in different regions vary from a low range of prices of 1,01 INR/m³ in Bhopal and 2,54 INR/m³ in Jabalpur and 4,72 INR/m³ in Indore in Madhya Pradesh and going up to 7,3 INR/m³ in Nashik and 11,16 INR/m³ in Nagpur in Maharashtra state (Ministry of Urban Development Government of India 2007). An average price over the regions was calculated after prices from 2005 were adjusted to inflation and 2016 prices using WPI (100= 2016). The water price used for valuating water consumption was set at 3,18 INR/m³. The water consumption is subtracted as disservice from the overall ESS value and calculated as follows:

(3) $$\textbf{ESS Value of water consumption}\ \frac{INR}{ha} = \textbf{ET}\ \frac{m^3}{ha} * \textbf{Water price}\ \frac{INR}{m^3}$$

Water use efficiency

As an additional parameter we calculated water use efficiency (WUE). Compared to the other parameters WUE is not part of the cost-benefit analysis evaluating the economic impact of different agricultural practices. However, it gives information on how effective a cropping system uses the available water to produce biomass. It serves as in indicator to highlight water efficient cropping systems. WUE is calculated as follows:

(4) $$\textbf{WUE biomass}\ \frac{kg}{m^3} = \frac{Biomass\ \frac{kg}{ha}}{ET\ \frac{m^3}{ha}}$$

In addition, we calculate a second water use efficiency indicator on the basis of the profit calculations. It tells us the net profit generated from one unit of water used (measured in evapotranspiration).

(5) $$\textbf{WUE profit}\ \frac{INR}{m^3} = \frac{\textbf{ESS Value of Yield}\ \frac{INR}{ha} + \textbf{ESS Value of byproducts}\ \frac{INR}{ha}}{ET\ \frac{m^3}{ha}}$$

Moisture storage

Moisture storage is essential for agricultural productivity. A common approach to evaluate soil moisture impacts is the valuation of water conservation based on water storage costs in a men mad reservoir. Several studies have conducted such an approach in the context of a forest ecosystems (e.g. Xue and Tisdell 2001; Biao et al. 2010; Mashayekhi et al. 2010; Ninan and Inoue 2013; Ninan and Kontoleon 2016). We could not find an example where the approach was used in the context of agricultural ecosystem service assessment. Still, we see no reason to reject the same logic in our context. We conduct a benefit transfer in order to value the water conserved in soil in different cropping systems. This approach has the great advantage of easy data availability and simplicity of modelling (King and Mazzotta 2000; Ninan and Kontoleon 2016).

The benefit transfer is conducted as done by Ninan and Kontoleon (2016) This study valued the water conservation of a national park from rainfall by estimating the water storage costs of a dam. The study site is not far away from our research area and we therefore use even Ninan and Kontoleon's (2016) values. They studied the Nagarhole National Park in Karnataka in India. The authors conduct an estimation of the value of rainwater conserved by considering the Kabini dam project which lies close to the national park. The calculated value of water stored in the dams is set at 0,03 INR/m^3. We use this price to estimate the value of soil moisture. The parameter simulated with APSIM that represents soil moisture is net water storage (NWS).The following equation was developed to estimate the value of moisture storage:

(6) $$\textbf{ESS Value of soil moisture}\ \frac{INR}{ha} = \textbf{NWS}\ \frac{m^3}{ha} * \textbf{Water storage cost}\ \frac{INR}{m^3}$$

Nitrogen fixation

Legumes like Chickpea and Soybean can fix nitrogen and improve nutrient quality in soils. This fixation of nitrogen can have a positive effect on plant growth and yields. Cropping systems have a big influence on the long term nutrient quality in soils. Hence, not by chance several studies have already assessed the value of nutrient budget in soils.

Ninan et al. (2016) examines the nutrient cycling and the benefit of accumulation of nutrients in an Indian forest. The authors first conduct a rough estimation of nutrients (NPK) accumulated in the forest and value those nutrients at the price of leaf manure in a nearby district, and at the market price of mixed chemical fertilizers in Karnataka state. The 2004 prices for leaf manure were set as 10 INR/kg and around 21,6 INR/kg for mixed fertilizer. A similar approach was conducted by Nahuelhual et al. (2007).

Lerouge et al. 2016 examines the sequestration value of N and P of different land use scenarios in Flanders in Belgium. The authors use marginal abatement cost for N and P based on De Nocker at al. (2010) and multiply those prices with the estimated amount of nutrients sequestered in the soil. Compared to Ninan et al. 2016 the authors chose a rather high cost range with 74€ kg/N and even 800 €/kg P.

Xue et al. (1999) also assesses nutrient cycling and the benefit of accumulating nutrients in the soil with an alternative cost and market price approach. The value of soil nutrients is estimated by multiplying maintained nutrient amount with the market price of fertilizer. The authors use a price for chemical fertilizers of 72,5 INR/kg (Caclulator Stock, 2017).

We take into account that N uptake of fixed N is higher than that of applied chemical fertilizer. The overall average proportion of the crop N derived from atmospheric N_2 across regions for different legumes is between 40 and 75 percent. Research now suggests N associated with nodules and roots may represent between 30% and 60% of the total N accumulated by legume crops (e.g. Rochester et aI. 1998; Mahieu et aI. 2007; McNeill and Fillery 2008) and studies indicate generally that <30% of the legume N is taken up by a subsequent crop (Fillery 2001; Crews and Peoples 2005.) The possibly lower average proportion of the crop N derived from atmospheric N_2 fixation can be attributed due to greater N mineralization of the soil organic N pool, as a result of elevated soil temperatures and higher moisture levels during crop growth (Maskey et aI. 2001).

Similar to the studies mentioned above, an alternative cost approach was chosen to estimate the value of nitrogen fixed in soil. The simulated amount of N fixed in soil is available for cropping systems including legumes. The value is calculated with the following equation:

$$\textbf{(1) ESS Value of N fixation } \frac{INR}{ha} = \textbf{N fixed } \frac{kg}{ha} * \textbf{N efficiency factor} * \textbf{ Fertilizer Cost } \frac{INR}{kg\,N}$$

The cost per kilogram nitrogen is calculated based on the assumption that DAP and Urea is applied in the ratio of 48:52. Considering the nitrogen contents of the two fertilizer varieties, which is 18% for DAP and 46% for Urea, the kg price of nitrogen is 139 INR/kg N for DAP and 13 INR/kg N for Urea.

We take into account, that the current prices of N in India are still highly subsidies. Currently, INR 20.88 is paid to companies per kg nitrogen they produce (GoI 2010, 2018). These are hidden costs to the society and should be taken into account when estimating the value of N fixation. We assume that farmers mainly use the cheaper Urea option and set the price per kg N to 13 INR/kg N plus 20.88 INR/kg. This estimate is considerably lower to the estimates of Xue et al.(1999).

Nitrogen leaching

Fertilizer application is a widespread method to improve agricultural productivity. The use of synthetic fertilizers has a positive impact on yield if applied effectively. However, inadequate or excessive fertilizer application can cause nutrient leaching. Especially leached nitrogen can harm off-site ecosystems such as downstream water bodies and lower water quality. This disservice appears when fertilizer application and irrigation management is not managed well. If animal and crop production are combined onsite, manure application can minimize nutrient leaching and also decrease the dependency on synthetic fertilizers provided that manure application happens at the right time and at reasonable amounts (Tilman et al. 2002)

In literature several approaches to valuate nitrogen leaching appear. Jenkins et al. (2010) and Ribaudo, Heimlich, and Peters (2005) assess the nitrogen mitigation potential of wetland restauration in the Mississippi Alluvial Valley, USA, in order to estimate a marginal price for nitrogen mitigation. Broekx et al. (2013) use the avoided abatement cost method to value nutrient removal from water bodies in Belgium. This is usually done by the natural process of denitrification. This study uses a benefit transfer from Nocker et al. (2010) setting a marginal nitrogen removal cost at 74 €/kg N in order to comply with a given water quality standard. Compared to studies with the same approach this cost is located at a very high range which varies between 2 - 70€/kg for N (Gren 1995; Börjesson 1999). Wei et al. (2010) assessed externalities arising from oasis farming in China. Here, for the disservice of nitrogen leaching the replacement cost method was chosen. Thus technology costs to reduce NO_3 concentrations in water artificially in a wastewater treatment plant are estimated at 1,6 yuan/m^3 (Fu 2008; Wei et al. 2010) which is around 21 INR/m^3 in 2017 prices.

The replacement cost approach can be considered as suitable and relatively easy to calculate for our study. Different to Wei et al. (2010) we do not focus on the costs of a wastewater treatment plant but on the costs of an artificial wetland. Several studies assess the capability of wetlands in India to purify water from pollutants (Billore et al. 1999; Jayakumar and Dandigi 2003; Billore, Prashant, and Sharma 2009).

Many studies highlight the potential of artificial wetlands for waste water purification; especially for developing countries as the system can be operated at low costs (Juwarkar et al. 1995; Billore et al. 1999; Kivaisi 2001; Jayakumar and Dandigi 2003; Massoud, Tarhini, and Nasr 2009; ElZein, Abdou, and ElGawad 2016). Billore et al. (1999) report treatment performance of a field-scale horizontal subsurface constructed wetland (CW) in central India. Removal efficiency reaches 58-65% for Phosphorus, Biological Oxygen Demand (BOD) and Total Kjeldahl Nitrogen (TKN) (Billore et al. 1999). Prashant et al. (2013) concludes that artificial floating reed beds reduce pollution load 45–50% of TKN (Billore, Prashant, and Sharma 2009)

Based on this experience in India, the valuation of nitrogen leaching will be done based on the costs to purify water with a constructed wetland. The most appropriate benefit transfer was found to be the costs reported in Billore, Prashant, and Sharma (2009) The study was chosen because it is recent and the study areas are comparable. Further the removal efficiencies lay within the range reported in other studies. In addition the study not only conducts an experiment design but actually implements the constructed wetland in practice in River Kshipra. Based on the costs mentioned in Billore, Prashant, and Sharma (2009) and the removal efficiencies for TKN we estimate removal costs of N per kg from a constructed wetland.

The study reports costs of 60 $/m² per floating island, 2 m² artificial floating reed beds (AFRB) were used which is 145,5 $ in 2017 prices and 24,5 $/a assuming a six year lifetime of the island. We use the removal rates from the experiment design with the mesocosms treatment of River water which are 45–50% of TKN including organic nitrogen and NH4+ in a 9 m³ tank over two months. We assume that the treatment is being repeated six times to get an estimation of TKN removal for one year. No maintenance costs are reported, however, we assume that benefits from free fodder obtained by the biomass production of the floating island compensated the costs. We use the following equation:

$$\textbf{(7) N removal cost} = \frac{\textbf{Island cost per year}}{(\textbf{TKN t0} - \textbf{TKN t1}) * \textbf{dwell time} * \textbf{Water treated}}$$

$$= \frac{\textbf{145,5\$ /12 months}}{\left(\textbf{53}\,\frac{\textbf{g}}{\textbf{m}^3 * \textbf{2 months}} - \textbf{29}\,\frac{\textbf{g}}{\textbf{m}^3 * \textbf{2 months}}\right) * \textbf{6 months} * \textbf{9m}^3} = \frac{\textbf{24,26 \$/a}}{\textbf{1296}\frac{\textbf{g}}{\textbf{m}^3 * \textbf{a}}} = \textbf{0,019 \$/g N = 1203 INR/ kg N}$$

$$\textbf{(8) ESS Value N leaching } \frac{INR}{ha} = \textbf{Nitrogen leached } \frac{kg}{ha} * \textbf{ N removal cost } \frac{INR}{kg\ N}$$

We agree that the cost estimated here are rather high. In India leached nitrogen usually does not affect surface water: However, in certain cases it affects groundwater. The nitrogen amounts leaching from the leaching profile into the hydrological cycle can be considered with few exception rather low in our study area. Therefore, we cut the costs that are estimated according to Billore et al. (2009) by multiplying this value by 5%. Thus for our evaluation we assume nitrogen cost of 60 INR/kg N.

Total organic carbon

Approximately 12-14% of anthropogenic GHG emissions are directly attributable to agricultural activities, without taking emissions from land clearings into account (Metz 2007). In order to draw conclusions on the mitigation dimension of climate smart agricultural practices it is necessary to assess the value of carbon sequestration related to different cropping systems.

A wide range of studies assessed the value of carbon storage or sequestration in different ecosystems (e.g Xue and Tisdell 2001; van Beukering, Cesar, and Janssen 2003; Croitoru 2007). Most studies focus on the carbon sequestration in forests as these are main carbon sinks (Tvinnereim, Røine, and Heimdal 2009; Badola et al. 2010; Lv, Gu, and Guo 2010; Nocker et al. 2010; Wei et al. 2010; Qian and Linfei 2012; Lerouge et al. 2016).

Other studies use marginal mitigation or social damage costs of carbon to monetize carbon storage. Nevertheless, none of those studies made estimates for South Asia (Jenkins et al. 2010; Wei et al. 2010; Gascoigne et al. 2011; Aertsens, Ninan and Kontoleon 2016). Another approach conducted in previous literature is done by Qian and Linfei (2012) and Ninan and Kontoleon (2016) that value carbon storage based on the costs of afforestation projects.

In this study the total carbon sequestration or release over a 30 year cropping system is valuated. A very common economic valuation method is to use the price of traded carbon credits in order to cover potential externalities that are related to carbon emissions (e.g. Lv, Gu, and Guo 2010; Nocker et al. 2010; Qian and Linfei 2012; Ninan and Kontoleon 2016).The World Bank Group summarizes current existing emission trading schemes and gives an overview of the current range of carbon prices for several countries. Carbon prices vary strongly between studies starting from less than 1 $/t CO_2 for the Shanghai

Pilot Emission Trading Scheme (ETS), as well as for Mexico and Poland. The highest prices for carbon credits are currently in Sweden, reaching a price of 137 \$/t CO_2 (World Bank and Ecofys 2017)

In contrast to many other countries, India has no carbon trading scheme yet. Nonetheless there are some studies that assess and recommend applicable carbon prices for India (e.g. Gera and Chauhan 2010; Aggarwal and Chauhan 2013). Both studies set 5\$/t CO_2 -10 \$/t CO_2 as a price to estimate all externalities related to carbon emission. We adapt the lower cost of 5 \$/t CO_2 which is around 337 INR/t CO_2. The value of total organic carbon (TOC) in soil is calculated as follows:

$$\textbf{(9)}\quad \textbf{ESS Value TOC } \frac{INR}{ha} = \textbf{TOC sequestered } \frac{kg}{ha} * \textbf{Carbon price } \frac{INR}{kg\ C}$$

Hidden costs of fertilizer production

In the calculation of the total ESS value, we take hidden costs associated with fertilizer production into account. These are on the one hand the aforementioned subsidies to fertilizer production of currently 20.88 INR/kg N (GoI 2010, 2018).

$$\textbf{(10)}\qquad \textbf{Fertilizer subsidy cost } \frac{INR}{ha} = \textbf{fertilizer applied } \frac{kg\ N}{ha} * \textbf{fertilizer production subsidy } \frac{INR}{kg\ N}$$

In addition, we take into account that the production of fertilizers demands much energy and generates considerable greenhouse gas (GHG) emissions (Wood & Cowie 2004). Based on the review of Wood & Cowie (2004) we use the indirect costs estimated by Davis and Haglund (1999). The latter estimate that approximately 4800g CO_2 are emitted per kg N produced.

$$\textbf{(11)}\qquad \textbf{GHG emission costs fertilizer } \frac{INR}{ha} = \textbf{fertilizer applied } \frac{kg\ N}{ha} * \textbf{GHG emissions fertilizer production } \frac{kg\ CO_2}{kg\ N} * \textbf{Carbon price } \frac{INR}{kg\ CO_2}$$

Methodology of data analyses

Five management packages consisting of variations of manure, fertilizer and irrigation application have been compared. The first package is modelled on the basis of the survey presented in Section *Results Farming System Analyses* above. By district and cropping system the simulations were run with reported input use level. The farmers' practice package was only modelled with historical climate data. In addition, we modelled the cropping systems with the amount of manure, fertilizer and irrigation as recommended by the Agricultural University, Rahuri/Maharashtra (GoM 2016).

In a next step we simulated an experiment, in order to see the response of the cropping systems to a reasonable variation of the management parameters. Table 24 shows the fractional orthogonal design for the simulated experiment.

We compiled a complete data set with all the modelled results. It contains a panel where the unique combination of cropping system, management package, climate scenario and location defines the panel identifier and the modelled year is the time identifier.

We analyze the data in a first step using graphical analyses and descriptive statistics. In a second step, we assume that the outcome variables are a function of the management, the climate, and the soil conditions.

Table 24: Taguchi's Orthogonal Array of the simulated experiment

	recommended irrigation		**1 irrigation less than recommended**	
	recommended fertilizer	**75 % of recommended fertilizer**	**recommended fertilizer**	**75 % of recommended fertilizer**
2.25 t manure		simulated	simulated	
3 t manure	simulated (recommended practice)			simulated

We assess these impacts calculating hierarchical Mixed-effects regression models. This econometric tool allowed us to considered structures in our date with regard to context layers at different scales. We further calculated averages of the outcome variables for each combination of cropping system, management package, climate scenario and location over the simulated years. The averages were analyzed using ordinary least square regression models.

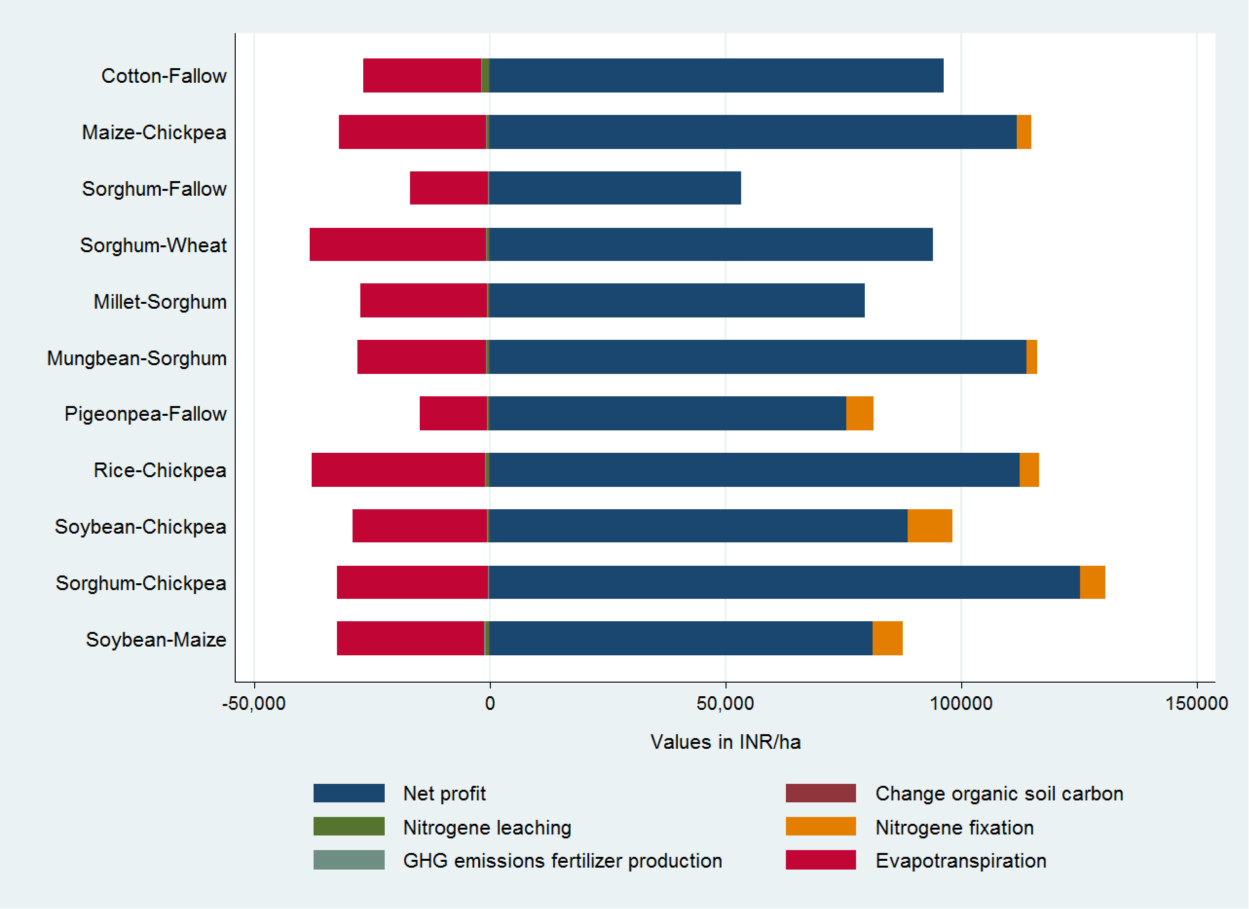
We took in our analyses into account that not all cropping systems are suitable at all locations. We used the District Socio-Economic Reviews of the Directorate of Economics and Statistics/Government of Maharashtra to identify which systems are grown in which areas (DoES 2014, 2013a-e, 2012, 2011, and 2009). Only for these areas the respective cropping systems were included in the analyses. Nevertheless, we also considered that may be some cropping systems are for path dependency reasons not yet cultivates in otherwise suitable environments. We therefore calculated by each location whether the average net profit for a cropping system was sufficient to move two people above the poverty line of USD 1.90. The cropping system was included in the analyses for the specific location if this condition was met.

Results

Figure 23 indicates that the provisioning ecosystem service of crop profits dominates the total ecosystem service value of most cropping systems at most locations. In the range of the assessed management practices and cropping systems and under the agro-climatic conditions of the study region, soil carbon fixation, soil moisture storage, nitrogen leaching or indirect greenhouse gas emissions related to fertilizer production are of minor value compared to the profit generated by the crop and its byproducts. Nitrogen fixation adds a notable benefit to the legume systems but is still low compared to the profits. The only remarkable hidden cost is the water used – measured in evapotranspiration. We will pay more attention to this aspect further below.

Figures 24 illustrates this pattern exemplary for the two cropping systems pigeonpea-fallow and soybean-maize. While the latter system has a higher profit per hectare the earlier one has a higher total ESS value. This is mainly due to the difference in water use.

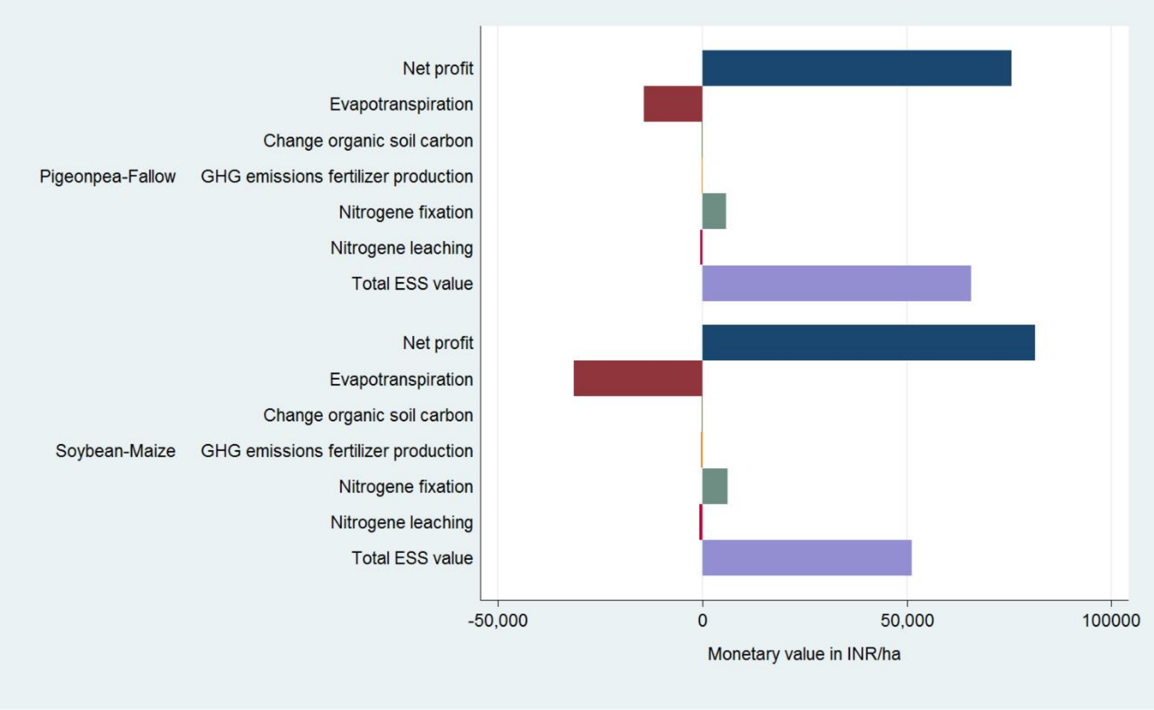
Figure 23: Bar chart of ecosystem service values in INR/ha by cropping systems (modelling results only for agro-ecologically suitable environments, based on simulation of recommended practice using past climate data); Note that the values below zero have to be deducted from the values above zero to arrive at the overall total ecosystem service value.



It is well documented that yields of non-legume crops can often be improved by including a legume in the cropping sequence. It was also observed from our study there was considerable N fixing was observed by including legumes in the system. It was also observed that the amount of N_2 fixation can also be improved with application of good agronomic principles as evident from our study. Following the recommended application of fertilizer and manure on average resulted in higher N_2 fixation values. Nevertheless, the economic value of N fixation was still relatively low compared to the profits.

Soil moisture storage may have a slight impact on the potential to grow Rabi crops and the requirement for additional Rabi irrigation. As in the current study we are calculating net water storage as difference between soil moisture during 1st day of monsoon crop and last day of post rainy season crop. The net water storage will give an indication on how much water is left in the soil after the 2nd crop in a system However it will not have any impact on the next year crop due to the extreme summer climate and the left over soil moisture is exhausted before the start of next year monsoon crop.

Figure 24: Exemplary comparison of means of different ESS indicators between the pigeonpea-fallow and the soybean-maize cropping system (modelling results only for agro-ecologically suitable environments, based on simulation of farmers practice using past climate data).



Nitrogen leaching: on average significantly higher amounts of nitrogen leaching beyond the root zone in the cotton system was observed compared to other systems. In some years we estimated that leached amount to exceed more than 100 kg/ha (yearly average app. 25 kg/ha) in this cropping system. Using our shadow prices (see above methodology of evaluating ESS impacts) the value of this hidden cost can exceed INR 13,000 per hectare. On average the nitrogen leached per year incurs hidden costs of approximately INR 2,000 under cotton production. The leached nitrogen is slightly lower when applying the fertilizer amount recommended by the Ministry of Agriculture (GoM 2016). Additional research is required in order to better understand under which conditions the leached nitrogen is really causing damage. This very much depends on the site specific hydrology and soil types. Most probable is a buildup of nitrogen in the ground water which can at a certain level diminish the water quality especially for human consumption. In some cases it is also possible that the nitrogen is transported through underground water to more distant water bodies. There is evidence that nitrate pollution is becoming more prevalent in groundwater of Maharashtra (Gupta et al. 2011).

We also took into account the greenhouse gas emitted during the fertilizer production. This indirect cost is a direct function of the applied fertilizer. There are significant differences between the cropping systems regarding this cost. In the mungbean-sorghum system in some years more than 1.5 tons of CO2 is estimated to be indirectly emitted per hectare. This is still equivalent to a small monetary value – at the carbon price assumed in our study (337 INR/t). Nevertheless, carbon price estimates still show a great variance (World Bank and Ecofys 2017) and assuming different prices would give this factor much stronger weight.

Figure 25 indicates that on average the sorghum-chickpea, mungbean-sorghum and rice-chickpea systems are most profitable across the environments of our study. The variation of the simulated profit is high especially for the cotton system. The median of the profit of the sorghum-chickpea is at a level which allows approximately four people to live above the poverty line of USD 1.90. The profit median of the least profitable system Sorghum-fallow would not be sufficient income for two people above the poverty line.

It is often argued that farmers do not maximize their profit but rather minimize risks. Figure 26 shows that the on average fairly profitable cotton system has the highest risk of crop failure. It is followed by the soybean-maize and millet-sorghum systems. The least profitable Sorghum-fallow system is the one least

Figure 25: Boxplots of net profit in INR/ha by cropping systems (modelling results only for agro-ecologically suitable environments, based on simulation of recommended practice using past climate data)

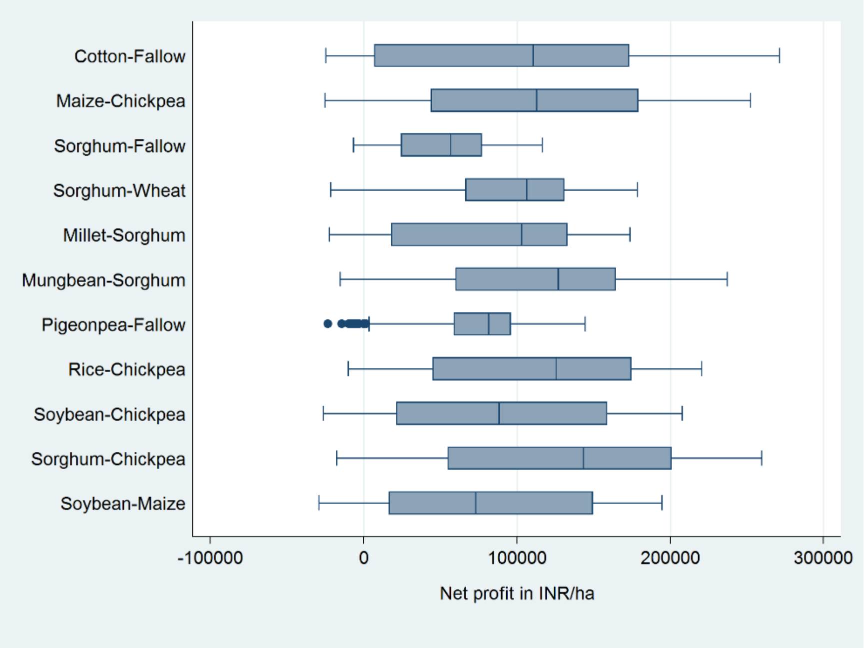
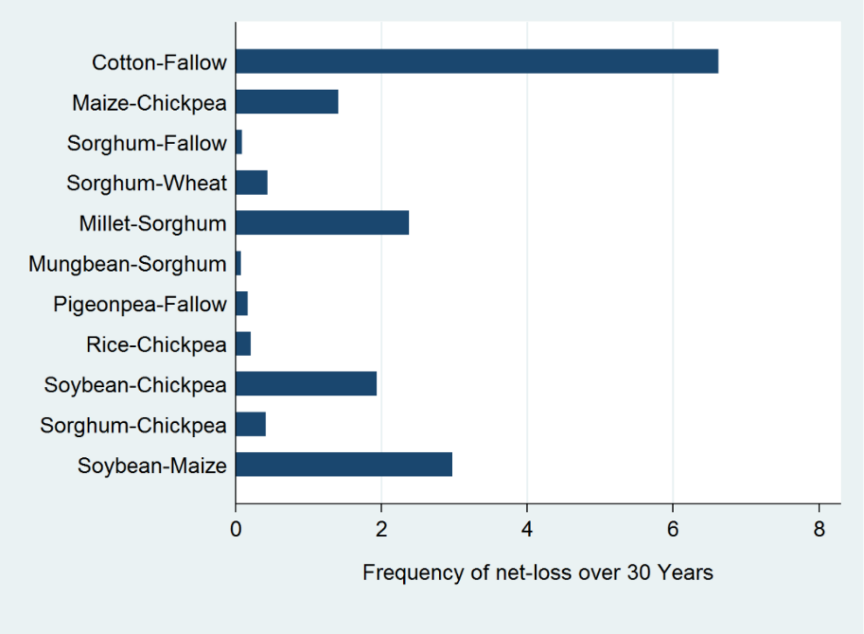


Figure 26: Bar chart of average frequency of years (out of 30 simulated years) when net profit is negative - by cropping systems (modelling results only for agro-ecologically suitable environments, based on simulation of recommended practice using past climate data)



likely to fail. Nevertheless, the most profitable systems of mungbean-sorghum and sorghum-chickpea are also quite unlikely to fail.

Figure 27 indicates that all cropping systems lead on average under the recommended practice to a loss in total organic soil carbon. The total value of this loss is low in comparison to the net profit. It is low even in absolute terms. Our GIS land use system analyses led to an estimated cropping area for the five studied districts of 52379 km^2. Assuming an average loss of 50 INR/ha per year results in approximately 4 Mio USD social loss due to soil carbon reduction for the whole study area. It is worth to explore how these costs can be avoided but it is a low number in overall economic terms. More important might be how the soil carbon loss is affecting the agricultural productivity. This needs to be further explored.

As mentioned before, significant hidden cost is the water consumed. Irrigation is by far the largest consumer of

Figure 27: Boxplots of value of changes in soil carbon over 30 simulated years in INR/ha by cropping systems (modelling results only for agro-ecologically suitable environments, based on simulation of recommended practice using past climate data)

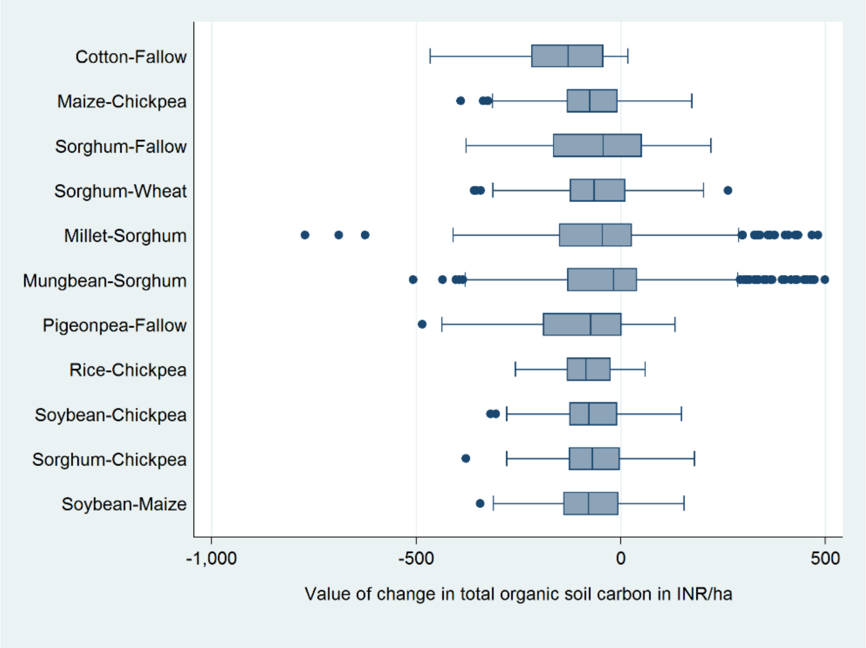
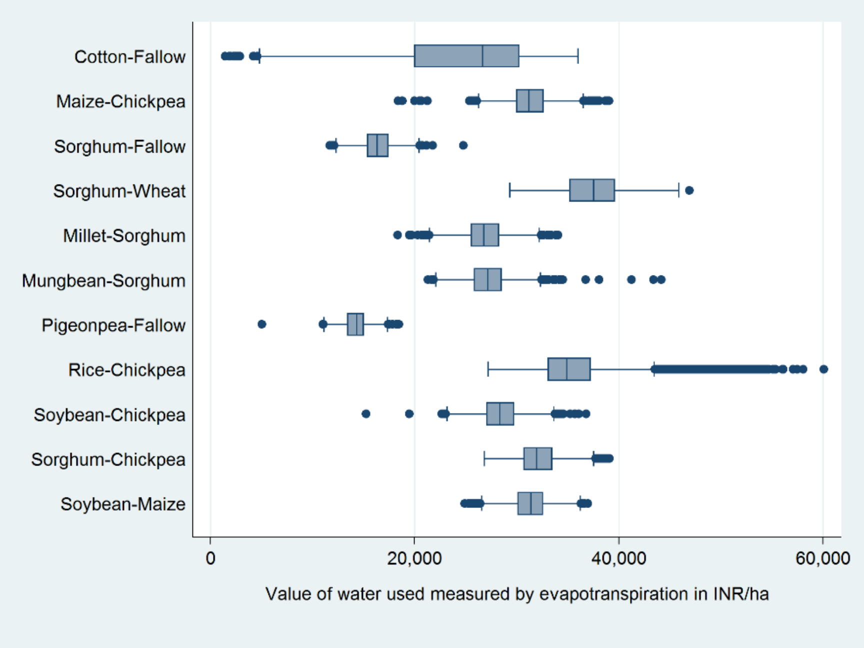


Figure 28: Boxplots of value of evapotranspiration in INR/ha by cropping systems (modelling results only for agro-ecologically suitable environments, based on simulation of recommended practice using past climate data)



freshwater in India. Close to 90 percent of all groundwater abstracted in 2010 was used in agriculture (Wada & Bierkens 2014). We measure the water consumption as evapotranspiration.

Figure 28 illustrates that the sorghum-wheat and rice-chickpea systems invoke the highest hidden water costs. The sorghum and pigeonpea fallow systems have the lowest water costs.

Figure 29 shows the value of nitrogen fixation. The double legume system Soybean-chickpea fixes the highest value of nitrogen.

The overall ecosystem service provision value is strongly dominated by the agricultural profit. The patterns of the net profit (Figure 26) and the total ecosystem service provision (Figure 30) look very similar. The sorghum-chickpea and mungbean -sorghum systems slightly gain in attractiveness especially in comparison to the rice-chickpea, maize-chickpea and cotton systems.

Figure 29: Boxplots of value of nitrogene fixation in INR/ha by cropping systems (modelling results only for agro-ecologically suitable environments, based on simulation of recommended practice using past climate data)

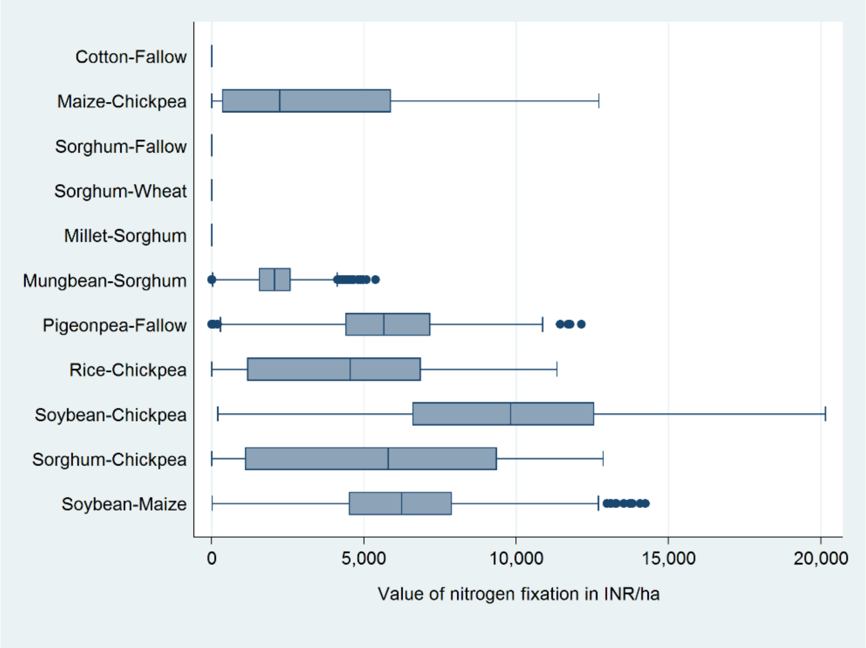
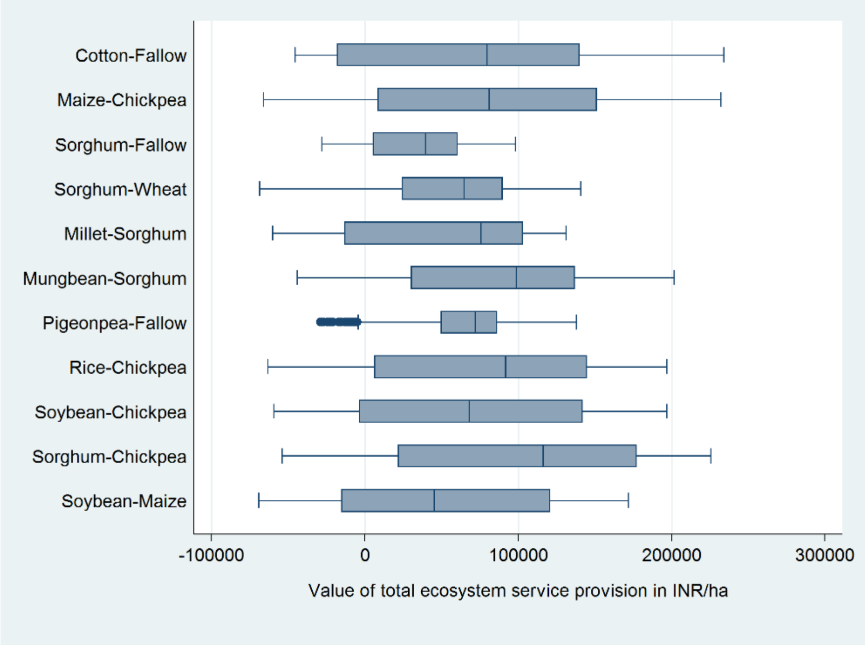


Figure 30: Boxplots of total value of ecosystem service provision in INR/ha by cropping systems (modelling results only for agro-ecologically suitable environments, based on simulation of recommended practice using past climate data)



In a next step we turn towards the results of our multi-variate analyses of the simulation data. We calculated a large number of models which can be found in the appendices.

Not to a great surprise, there are general patterns regarding the impact of different soil types across cropping systems. The Models in the Appendices 1a to k and 3a to k suggest the following order of attractiveness of soil types:

1) Very deep vertisol
2) Deep vertisol
3) Deep entisol
4) Very deep inceptisols
5) Slightly deep entisols
6) Shallow inceptisols
7) Slightly deep inceptisols
8) Very shallow entisols
9) Very shallow inceptisols
10) Extremly shallow entisols.

The mungbean-sorghum system is amongst the most profitable and best systems in terms of ESS provision across all soil types, agro-ecological zones, and climate scenarios (Appendices 4b, 5a, 6a-c, 7a-c, 8a-j). It ranks amongst the highest for ESS provision and profit per unit water used across all climate scenarios (Appendices 4b, 4c, 5b & 5c). The system has a higher probability of crop failure in semi-arid (dry) environments without affecting the average profit negatively (Appendix 3f). Still, its comparative advantage is highest in dry environments (Appendix 6a-c, 7a-c). The system would gain in comparative advantage under the hot-dry climate scenario (Appendices 2f & 3f). Increasing manure, fertilizer and irrigation has a positive impact on profit, ESS provision and Water use efficiency of the mungbean-sorghum system (Appendices 1f & 2f).

The pigeonpea-fallow system performs best in terms of profit, ESS provision and water use efficiency in semi-arid(dry) environment (Appendices 6a & b). It would gain in attractiveness under both climate scenarios (Appendices 2g & 3g, 4b). The pigeonpea-fallow system positively reacts to irrigation while lower fertilizer and manure are actually better in terms of profit, ESS value and water use efficiency (Appendices 1g & 2g).

Sorghum-chickpea is amongst the most attractive systems on very deep vertisol, deep vertisol, deep entisol, slightly deep entisols, shallow inceptisols but not for instance on extremely shallow entisols or very shallow inceptisols (Appendices 8a-j). The system performs best in sub-humid environments (Appendix 3j, 6a, 6b, 7b). It rank amongst the highest in terms of net profit, ESS provision and profit per unit water used across all climate scenarios (Appendices 4a-c, 5a-c). It would still benefit from both future climate scenarios – more strongly even from the hot dry one (Appendices 2j & 3j). Increasing manure, fertilizer and irrigation has a positive impact on profit, ESS provision and Water use efficiency of the system (Appendices 1j & 2j). The recommended manure, fertilizer and irrigation gives best values across the indicators (Appendix 3j).

The sorghum-fallow system is in the dryer environments across most soil types (except very deep vertisols) giving very high profits per unit of water used (measured in evapotranspiration) (Appendices 4c, 5c, 6c, 7c, 8a - j). On all the better soil types (e.g. very deep vertisol, deep vertisol, deep entisol, very deep inceptisols) the system is compared to other systems very poor in terms of profit and ESS value (Appendices 8a, 8b, 8g, 8h). Nevertheless, on slightly deep entisols and slightly deep inceptisols it is amongst the top systems in terms of total ESS value (Appendix 8d, 8e, 8f). On very shallow and extremly shallow entisols as well as very shallow inceptisols, sorghum-fallow is even amongst the top profitable systems (Appendix 8c, 8i, 8j).

Increasing manure and fertilizer has a positive impact on net profit, ESS provision and water use efficiency of the sorghum-fallow system. Irrigation has no significant impact (Appendices 1c & 2c). The recommended manure, fertilizer and irrigation gives best values across the indicators compared to the other modelled management practices (Appendix 3c). The sorghum-fallow system performs best in the semi-arid (moist) environment (Appendices 2c & 3c). It would improve its performance under the hot-dry climate scenario while the cool-wet one more likely had a negative impact (Appendices 2c & 3c).

Cotton is amongst the top three systems in terms of profit on deep vertisol and very deep inceptisols (Appendix 8b, 8g). In the range of the modelled management practices the cotton-fallow system negatively reacts to fertilizer and irrigation (Appendices 1a and 2a). The system would benefit from the hot-dry climate scenario while the cool-wet one more likely had a negative impact (Appendices 2a and 3a).

Sorghum-wheat is amongst the top three systems in terms of profit on slightly deep inceptisols (Appendix 8e). Increasing manure, fertilizer and irrigation has generally a positive impact on profit, ESS provision and water use efficiency of the sorghum-wheat system (Appendices 1d and 2d). The recommended manure, fertilizer and irrigation gives best values across the indicators (Appendix 3d). The sorghum-wheat system would be negatively affected by both climate scenarios (Appendices 2d and 3d). The system is rather poor in terms of water use efficiency (Appendix 4c, 5c, 6c, 7c).

Maize-chickpea, soybean-chickpea and rice-chickpea are amongst the best systems in terms of net profit and ESS provision only on the best soils (very deep vertisol) (Appendix 8h) and under sub-humid conditions (Appendices 6a, 6b, 7b). All three systems are rather poor in terms of profit per unit water used especially in dry areas (Appendix 6c). For rice-chickpea the combination with sub-humid climate works best (Appendix 6a) where it is amongst the most profitable systems across all climate scenarios (Appendix 5a). Still, even under these conditions the rice-chickpea is at best average in terms of profit per unit of water used (measured in evapotranspiration) (Appendix 6c). Increasing irrigation further deteriorates the profit and water use efficiency of this system. Increasing manure and fertilizer contributes to higher profit and ESS value (Appendices 1h & 2h). Rice-Chickpea would lose under the cool-wet climate scenario but gain under the hot dry one (Appendices 2h, 3h, 5b). Under this climate scenario it would win attractiveness compared to the otherwise more profitable sorghum-chickpea system (Appendix 4a).

In the range of our modelled management options, an increase in irrigation increases the net profit and total ESS value of the maize-chickpea system. Increasing fertilizer application improves profit but decreases the total ESS value (Appendices 1b & 2b). The cropping system grows better in the sub-humid environments (Appendix 3b, 6a). The maize-chickpea system would be positively affected by the cool-wet climate scenario (Appendices 2b, 3b & 5a).

The soybean-chickpea system grows best in wetter environments (Appendix 3i) even though it would improve its performance under the hot-dry climate scenario (Appendices 2i and 3i). Increasing irrigation positively affects profit, ESS values and water use efficiency. Increasing fertilizer application has a negative impact (Appendices 1i & 2i).

The millet-sorghum system has no comparative advantages under any of the simulated environmental conditions. There are no significant differences in absolute terms in its performance between the agro-ecological zones (Appendix 3e). Increasing manure, fertilizer and irrigation has a positive impact on profit, ESS provision and Water use efficiency of this system (Appendices 1e & 2e). The recommended manure, fertilizer and irrigation gives best values across the indicators (Appendix 3e).The system would be positively affected by both climate scenarios, especially by the hot dry one (Appendices 2e & 3e).

Across all cropping systems and agro-ecological zones, our simulations indicate that on average the agricultural sector would gain in terms of productivity and ecosystem service provision under the hot-dry climate scenario. Under the cool wet scenarios, profits and ESS provision would be reduced in sub-humid areas (Appendices 7a-c).

In a last step of the analyses we illustrate the spatial impacts of different management and climate scenarios using maps (see Appendices 9 to 24). The maps give the impression that the impacts of management and climate scenarios on the net profit and the ecosystem service value is to small and too context specific to reveal significant spatial pattern. Appendices13 and 14 illustrate that the sorghum-wheat system promises higher profit and ESS values in the areas where it is grown when increasing manure, fertilizer and irrigation according to the official recommendation. Appendices 23 and 24 further indicate that the same system would lose profitability under the hot-dry climate scenario. These effects are most pronounced in parts of Amravati and Ahmednagar. Appendices 21 and 22 indicate that the Millet system would suffer in terms of ecosystem service provision from the hot-dry climate scenario. We see this in particular in Yavatmal. In contrast, the Pigeonpea system would rather benefit in the far south of Yavatmal from a hotter and dryer climate. Appendices 23 and 24 show that the rice system would become more profitable in central Ahmadnager under the hot-dry climate scenario. The same can be expected for the soybean-pulse systems in north-east Amravati.

Discussion

Our analyses first of all reveal that the overall ecosystem service provision is dominated by the agricultural profit and the hidden cost of water consumption. All other ESS indicators considered in our study play a minor role. Even if these results are based entirely on simulation models, we believe these results are a good enough reason to focus empirical ESS assessments in the context of agricultural land use in Maharashtra/India on yields and water use.

Our results confirm the overall positive effect of manure on all observed ecosystem service indicators across different agro-ecological environments, cropping systems and climate scenarios. This is the more remarkable as our models cannot capture all the benefits manure provides to soils and agriculture. It remains, however, a question how so much manure can be made available. Approximately 15 megatons of manure would be required and distributed per year to apply 3 t per ha to the total cropping area of our study region.

Fertilizer and irrigation have more differentiated effects on profits and ESS provision. The effect of irrigation is strongest in dry environments but turns rather negative in wetter areas. It might still improve yields but taking associated costs into account it is often more profitable to reduce irrigation. This effect would even become stronger if the water itself was priced.

Mainly due to differences in water consumptions, we can find examples where increases in yields come at the cost of significant ecosystem service losses. Famers and extension officers often state that water is the most critical constraint for agriculture. If this was true, the question emerges why the focus does not shift from land productivity to water productivity. Our simulations show for instance that the sorghum-fallow cropping system promises in most environments poor net profit per ha but highest net profit per water unit evapotranspiration. The system has in particular comparative advantages on poor soils and dry environments where it performs even better than most other cropping systems in terms of profit per ha. Under more favorable agro-ecological conditions cropping systems like cotton, maize-chickpea, soybean-chickpea and rice-chickpea outperform the sorghum-fallow system in terms of profits per ha but not in terms of profit per water unit used. It is not our intention to promote specific cropping systems. We only want to raise awareness on the hidden costs of water use. Especially in areas with strong water scarcity, distributing water over a larger area, growing water use efficient cropping systems which are less profitable per hectare, can increase the overall agricultural production of that area. The challenge is, however, that farmers make individual decisions and water often has the feature of sequential access. In other words, often these hidden costs are not experienced by the farmer but e.g. by downstream water users. If the first farmers take as much water as is required to grow more profitable but less water use efficient crops than overall social welfare may be negatively affected. Such situations would be of interest of a policy maker who is interested in society’s welfare at the large scale. Governance mechanisms to include such undesired effects into local decision making are difficult to find on the local scale. This can even economically justify subsidies which provide incentives for ecosystem smart land management or for maintaining minor irrigation infrastructure.

The scale of the water use problem depends on the shadow prices set for the hidden cost. Giving evapotranspiration a monetary value is a challenging task in India. We decided to use water prices of water utilities as orientation for setting the water prices. We are aware of the limitations of this approach. On the one hand we are comparing in this way urban drinking water prices with rural water supply. On the other hand, water prices from utilities are highly subsidized. We assume a price of 3.2 INR/m³ which is rather at the lower end of prices in different towns and cities. Using this price we find that on average the Maize-Chickpea, Sorghum-Chickpea, Pigeonpea single crop, Greengram-Sorghum, and cropping systems have the highest total profit per unit water used (Figure 65). Typically, the hidden water costs are in the range of one Third of the total profit while they can exceed the profit e.g. in the Sorghum-Wheat system (see Figures 66 & 67).

There are reports about emerging rural water markets in India (Saleth 1998). It can, however, be asked whether these are really water markets or rather markets for providing transportation services of water. The farmer who is lifting the water is not paying for the water but only has the investment and operational costs of storing and moving the water. We acknowledge that in the process of moving the water a privatization of the water takes places and eventually water is sold on the basis of demand and supply. The informal local markets for water supply are little transparent. Our explorative assessments showed diverse payment practices. We found examples for payments per irrigation event ranging from INR 1200 to 2500 per hectare. Another payment system is to give the water supplier one Quarter of the harvest. Yet another system is the provision of labor to the water supplier. The exemplary evidence suggests water price ranges between 2.5 and 5 INR/m³ which we believe is consistent with the value set on the basis of water facility prices. Even if these prices are not really prices for the water itself, they indicate a remarkable willingness to pay for water.

Another option for setting water prices could be the fees charged for using canal irrigation water. Charges are typically calculated per hectare and depending on the type of crop grown. As per the revised water rates for different crops grown under canal system irrigation (GoM 2011) the charges range from INR 240 per hectare per season in case of kharif food crops up to INR 1350 per hectare for cotton. Using the evapotranspiration estimated in the model simulations this results in water prices of on average 0.1 INR/ m³ for kharif and 0.06 INR/ m³ for rabi irrigation. Such highly subsidized prices can only be seen as a gift to farmers. They are neither likely to create sufficient revenue for maintaining the infrastructure nor to encourage efficient use of water. Looking at the payments which are made between neighbors for supplying water, they also seem not to reflect many farmers' willingness to pay for water.

We also used another approach for estimating a shadow price for water which was based on the assumption that saved water could be used for irrigation in the Rabi season to grow an additional water use efficient crop on otherwise fallow land. Especially on deeper soils the average water use efficiency in terms of total profit per m^3 can get close to values of 30 INR/m³ for chickpea. If we used this as a shadow price for evapotranspiration hardly any cropping system would produce a positive total ecosystem service value. Therefore we believe that our value of 3.2 INR/m³ is rather a conservative water shadow price.

The impact of soil fertility enhancing technologies on productivity and household incomes

The Sustainable intensification of agriculture production systems has multiple challenges. Small holder farmers with limited resources (land, finance and labour), poor market access and limited infrastructure in the developing countries can find an opportunity to improve production systems, when small farmers are incentivized suitably. The complex problems of the developed world has been that further improvements in production systems becomes uneconomical and too risky (Sadras and Rodriguez, 2010) or inconsistent with environmental outcomes.

In India 41 percent of the rural poor live in SAT regions with the majority relying on agricultural activities for their livelihoods. Rainfed agriculture is a typical land use system in semi-arid tropics (SAT). It is particularly vulnerable to climatic and socio-economic stresses. Maharashtra state in India is having the largest area of drought-prone agricultural land in India (Udmale et al 2014). Increased temperatures, altered seasonal precipitation patterns (amount, timing and distribution) and increased risk of severe weather events have serious impacts on agriculture, water resources, agro forestry and wellbeing of livestock and human population. Livelihood of around 65% rural population of this region is dependent on agriculture and allied activities (Udmale et al 2014). Severe land degradation, low and unstable crop and livestock productivity are major challenges of smallholder rainfed (dryland) agriculture in Maharashtra. Increasing climatic variability further threatens food security and sustainability of these farming systems and associated livelihoods.

Hence the design of more productive, profitable and sustainable farming systems, require more integrative systems modelling approaches to choose best combination of management variables that influence the crop yields of individual fields, and the way limited resources are allocated across enterprises and fields at the whole-farm level (Rodriguez et al. 2011; Power et al. 2011). Systems modelling embeds bio-physical, crop eco-physiological principles that account for local constraints on resources, socio-economic, and value chain factors. At present, development and extension projects which support co-learning and practical management decision-making, systems modelling has been suggested as a useful approach (McCown 2009). Models are essential tools as they can integrate the effects of change of context (i.e. inputs, prices and policy) and of systems and calculate multiple indicators at different scales for the different sustainability domains (economic, social and environmental) (van Ittersum et al., 2008). The multifunctional nature of agriculture is increasingly recognized and that different stakeholders with different objectives (i.e. agricultural production, soil fertility, natural conservation and employment) and interests require systems modelling approaches to evolve suitable farming systems in a region. The use of systems modelling tools is being accelerated to identify farming systems that are best suited to a particular region.

The aim of this initiative is to evaluate a range of alternative farm systems and soil fertility enhancing technologies from production, economic and environmental perspectives using systems analysis tools. The results of this work will be used to assess the economic impacts of sustainable soil management approaches with the intention to provide arguments for farmers, policy makers and other important actors to promote soil protection and rehabilitation of degraded soils across scales. We are trying to understand the impact of cropping systems and soil fertility management practices on selected ecosystem services in the context of semi-arid areas in the Maharashtra and Madhya Pradesh states of India.

Here the aim was to develop modelling platforms (household, crop and livestock) to better understand temporal and spatial dynamics and therefore risk. These systems tools will help scientific professionals and extension agents to effectively evaluate a range of alternative farm systems from production, economic and environmental perspectives. Systems analysis, encompassing the biophysical and socio-economic makeup of farm households, uses a range of systems tools can capture some of these complexities (Keating et al. 2003; Lisson et al. 2010; Komarek et al. 2012) and help in devising robust intervention strategies which more effectively lead smallholders out of poverty and enhance ecosystems services. The results of this work will directly feed into the Economics of Land Degradation study.

Data and Methodology

We follow a three-pronged approach to explore the whole-farm tradeoffs associated with different farming systems and a range of interventions in terms of organic manure utilization, following fertilizer recommendations, and lifesaving irrigation through harvested water.

Data and Benchmarking Farming Systems

We begin with identifying existing farming systems in each of the five districts from biophysical, economic and cultural perspectives. By deriving and overlapping information from Geospatial analysis, secondary crop production statistics and in-depth farm household surveys we benchmark two predominant farming systems within each of the five clusters/districts.

After defining the farming systems we collate information from the household surveys in each of the clusters to inform key features of the farm-household system that include:

Resource endowments: Land and Labour

Income generating Crop and Livestock activities: Crop types, Area, Number of Livestock, Input-Output details, Input Costs, Output Prices etc.

Others: Farm Overheads, Household Expenses, Credit, Non-farm income etc.

Simulating Crop and Livestock Production

In the next step we derived simulated crop production using the APSIM farming systems model that simulates crop, forage and soil-related processes dynamically in response to weather and other management factors on these processes using local climate and soil characterization data. The model captures variability and production risks due to seasonal climate variability in long-term systems simulations.

We also simulate livestock growth and reproduction resulting from quality and quantity of feed availability from different farming systems using the livestock growth model within the Integrated Assessment Tool (IAT) (McDonald et al., 2004).

Integrated Assessment Tool to explore Whole-Farm Economic Trade-offs

We use the Integrated Assessment Tool (IAT) which is a whole farm model to capture key economic and biophysical processes and their interactions in the smallholder farming system. The main advantage of the IAT is that it integrates three separate models: APSIM (a farming system model), Livestock growth model and a whole-farm economic model. The Integrated assessment tool therefore is an integrated crop–livestock-household model, with dynamic linkages among crop, livestock, and socioeconomic components.

Simulated crop and livestock production data from APSIM and Livestock model within IAT are used to examine production trade-offs associated with different farming systems in different districts. Using IAT we assess the competitiveness of a range of competing crop-livestock enterprises/combinations and best management strategies and their impacts on whole household cash flows and on risk management plans considering climatic variability, labour availability, land holdings and other socio-economic constraints. In our whole farm trade-off analysis we examine the following scenarios:

1. *Farmers practice (FP):*
   Existing crop-livestock mix and input level use
2. *FP+ Integrated intervention*:
   Application of organic manure, fertilizer and irrigation interventions (only in selected cases) with existing crop-livestock activity mix
3. *New enterprise mix*:
   Context specific modified crop-tree-livestock mix with current level of input use
4. *Modified crop-tree-livestock mix +Integrated intervention (II)*:
   Application of organic manure, fertilizer and irrigation interventions (only in selected cases) with suggested crop-livestock activity mix

Results

We converge data from geospatial analysis, crop growth simulation models, detailed household surveys and expert knowledge to assess the impact of current practices and various soil fertility enhancing interventions on crop yields and other ecosystem services (ESS). These include provisioning and regulating ecosystem services which are more strongly affected by cropping and soil management practices such as: harvested yield, by-products at maturity (fodder, crop residues), water use efficiency, drainage, soil loss on a plot basis, biological nitrogen fixation (BNF), potential nitrogen leached, total organic carbon sequestration. In particular, tradeoffs between suggested interventions and current practices on crop yields and household level cash flows are analyzed using IAT. In the following sections we give an overview of the regional differences in the land and livestock holdings and farming systems.

Land and livestock holdings

The average land and livestock holdings across the five districts are presented in Table 25. Land and livestock endowments vary significantly among the districts and ranges between 1.27 ha to 3.51 ha. Yavatmal district accounts for the highest average land holdings size with 3.51 ha followed by Jalna (2.78

ha), Amravati (2.59 ha) and Ahmednagar (2.33 ha), with Dhule having the lowest landholding size of 1.27 ha.

Average livestock holdings in all of the five districts is low. Goat and milch cattle including buffaloes and cows are common in all the districts. Most of milch cattle are low yielding, except for those in Ahmednagar and Jalna.

Table 25: District wise average land and livestock holding

Districts	**Average land holdings (Ha)**	**Average Livestock holding (No)**			
		Bullocks	Goats	Milking buffaloes	Milking cows
Ahmednagar	2.33	1	2.5	1	2
Amravati	2.59	0	1	0	1
Dhule	1.27	2	3	1	1
Jalna	2.78	1.5	1	1	1
Yavatmal	3.51	2	1.5	0	2

Regional Farming Systems & Proposed Interventions

Table 26 gives an overview of two predominant regional farming systems across the five districts and lists common intervention practices that are introduced into the baseline farming systems.

Table 26: District wise Farming Systems and Interventions

District	**Cropping System 1**		**Cropping System 2**		**Perennial**
	Kharif	Rabi	Kharif	Rabi	
Ahmednagar	Greengram	Sorghum	Fellow	Sorghum	--
	Maize	Chickpea	Cotton sole	--	--
	Millet sole	--	--	Onion	--
	--	Onion	--	--	--
Amravati	Soybean+Pigeonpea	--	Soybean+Pigeonpea	--	--
	Soybean	Chickpea	Soybean	Chickpea	--
	Cotton+Pigeon	--	Sorghum	Wheat	--
Dhule	Paddy	Chickpea	Soybean	Chickpea	--
	Soybean	Wheat	Maize sole	--	--
		--	Cotton sole	--	--
Jalna	Soybean	Wheat	Soybean	Wheat	--
	Maize Sole	--	Cotton+Pigeanpea		Pomegranate
Yavatmal	Soybean	Chickpea	Sorghum	Wheat	--
	Cotton+Pigeonpea	--	Cotton+Pigeonpea	--	--
	Sorghum	--	--	--	--
Common Interventions	1. Recommended Nitrogen				
	2. Recommended manure (FYM)				
	3. Lifesaving irrigation (only on selected crops)				
	4. Better integration of livestock (No. & Breed)				

In a next step we present results on measures of whole-farm system economics for both identified baseline farming systems (farmers practice) and associated interventions (integrated interventions) into the same. Apart from the predominant regional farming systems we also present an alternative crop-livestock Scenario that incorporates crop pattern and area changes, livestock intensification, introduction of perennial tree components etc. for each of the farming system to examine production and economic trade-offs at crop, livestock and whole-farm level.

Ahmednagar

Farming System -1

Crop production in this type of system on a total area of 2.3 ha consists of Green gram, Maize and Millet in the Kharif season, followed by Sorghum, Chickpea and Onion in the Rabi season. Households have a diverse mix of livestock portfolio, including better yielding milch cattle (1 buffalo and 2 cow) along with a few goats.

The average production outcomes for various crops associated with the introduction of integrated interventions-organic manure, fertilizer and irrigation interventions into this farming system are represented in Figure 31. Incorporating integrated interventions in Green gram crop has increased costs by 2.5% but delivered a 22% increase in net profits. However in the case of Sorghum and Millet, net profits have decreased by 60% and 8% with integrated interventions associated costs rising by 8% and 3% respectively. However, the whole-farm net profits slightly increase by 4% as compared to the Farmers' practice with no interventions.

Figure 31: Ahmednagar 1 cropping systems scenario analysis

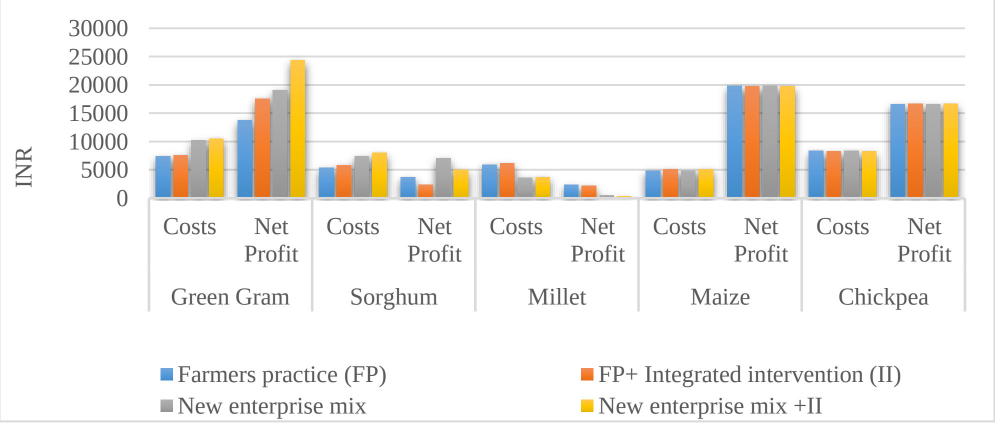
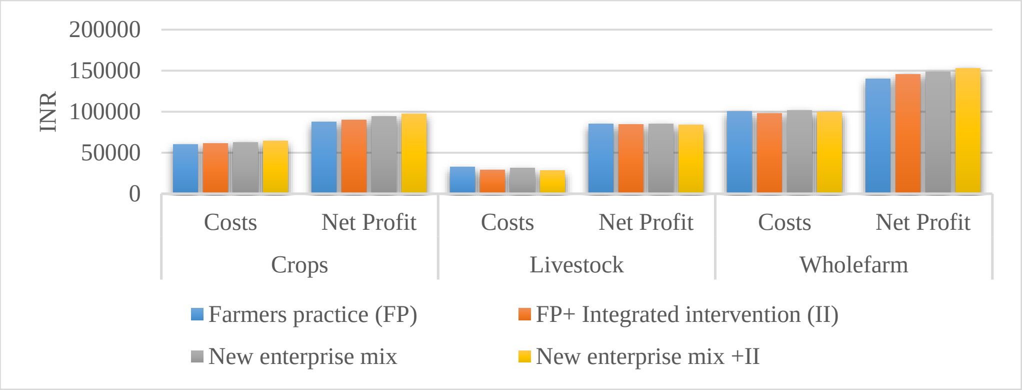


Figure 32: Ahmednagar 1 whole farm scenario analysis



In an alternative scenario, we try to model crop land-use changes in the system by increasing area under Green gram and Sorghum and by decreasing area under Millet. The average costs increase by around 2% giving up to 6% increase in profits as against the Farmers' practice-the baseline farming system (Figure 32).

The labor efficiency ratio however is much higher in the Farmers' practice as compared to the alternative scenario. The fodder availability is higher in both the systems when we incorporate fertilizer and irrigation interventions as opposed to the Farmers' practice.

Farming System -2

This farming system with total area of 2.3 acres is characterized by cultivation of Fallow-Rabi Sorghum and Kharif Cotton as the main crops, along with Onion. Households in this farming system also have a diverse livestock that includes better yielding milch cattle (1 buffalo and 2 cows) and a few goats. Incorporating recommended organic manure, fertilizer and irrigation (integrated interventions) into this farming system has increased net profits in Cotton and Sorghum by 36 % and 51% respectively with no cost increase in Cotton and about 15% cost increase in Sorghum (Figure-33).

Figure 33: Ahmednagar 2 cropping systems scenario analysis

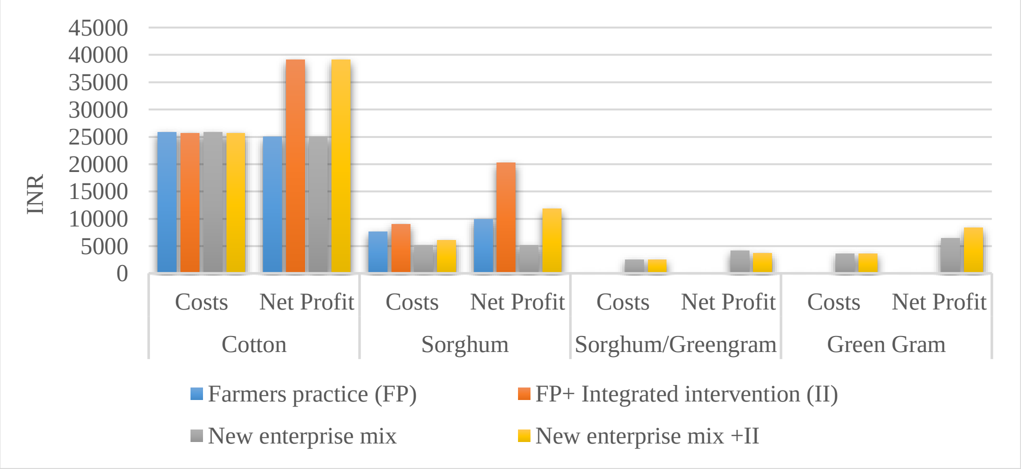
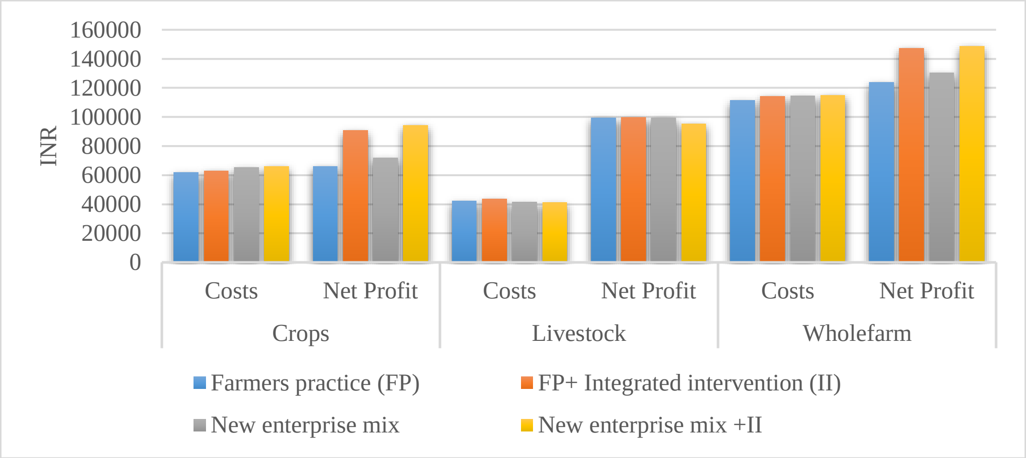


Figure 34: Ahmednagar 2 whole farm Scenario-Analysis



In an alternative crop system scenario we introduce Green Gram as a Kharif crop followed by Sorghum in Rabi replacing area under only Fallow Sorghum (Figure 33). The overall whole-farm profits in this scenario have increased by 5% compared to the Farmers' practice, with majority share of profits coming from the crop production. Changes in fodder availability were negligible (Figure 34).

Amravati

Farming System - 1

With an average land size of 2.6 ha, the predominant farming system in this district consists of Kharif Soybean followed by Rabi Chickpea, Kharif Soybean and Cotton with Pigeon Pea as an intercrop. Households have very low yielding milch cattle (1 cow) and a goat.

The application of organic manure, fertilizer and irrigation interventions have further decreased net profits in Soybean by 10%. Costs have risen between 1% and 8% in other crops like Cotton, Chickpea, and Pigeonpea with decreasing net returns to the extent of 1% to 3.5% in these crops. The associated increase in costs to incorporate integrated interventions have plunged the whole farm net profits (Figure 35).

Figure 35: Amravati 1 cropping systems scenario analysis

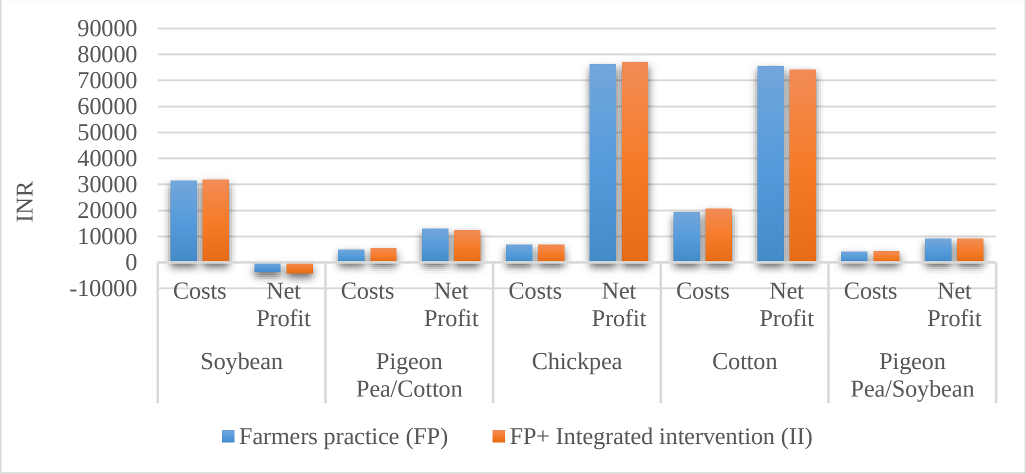
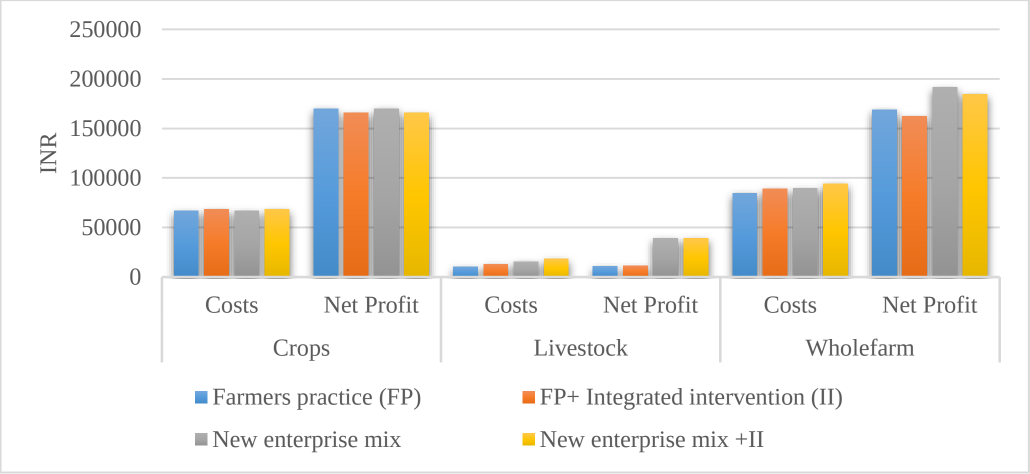
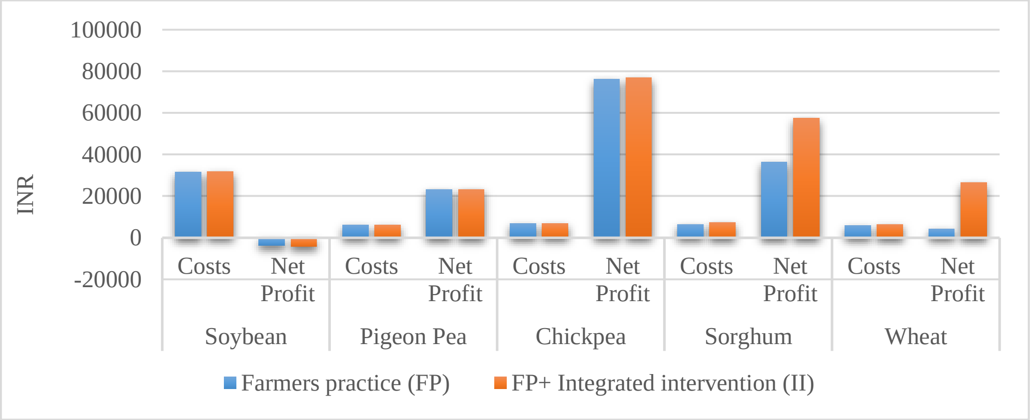


Figure 36: Amravati 1 whole farm scenario analysis



The average milk yield of cows in this district are very low at 1.5 litres per day and there is a considerable amount of fodder available that can sustain the needs of a better yielding cow capable of producing an average milk yield of 10-11 litres per day. So in a possible scenario we introduce high yielding cow into this system replacing the low yielding cow. This increases the whole farm net profit by more than 12% (Figure 36) from the Farmers' practice (baseline farming system) with almost zero associated costs.

Figure 37: Amravati 2 cropping systems scenario analysis



Amravati

Farming System -2

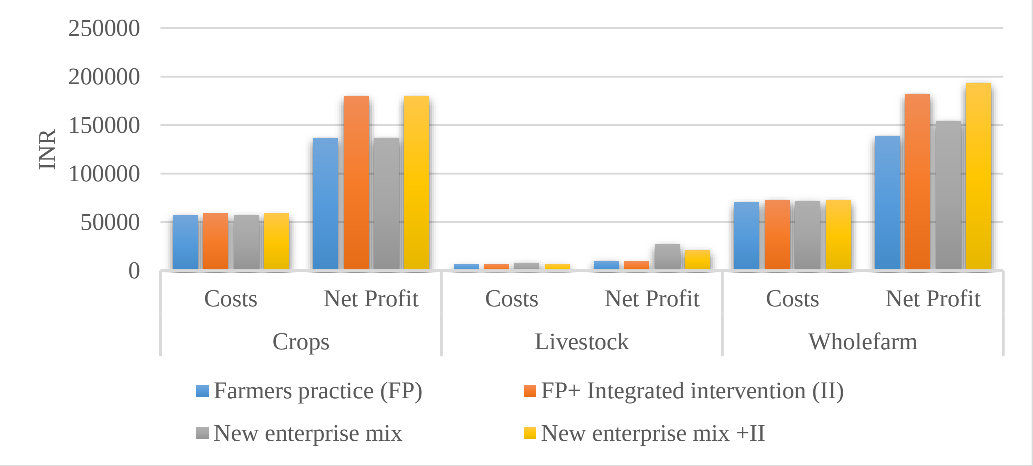
Following the same land size of 2.6 ha, crop production in this system consists of Kharif Soybean followed by Rabi Chickpea, Kharif Soybean with Pigeonpea as an intercrop and Kharif Sorghum followed by Rabi Wheat. Households have very low yielding cows and a few goats just as in farming system 1 of the district.

While Soybean follows a similar trend to that of farming system-1 in delivering further decreased net profits to an extent of 10%. Sorghum and Wheat cropping system generate 36% and 84% higher net returns when organic manure, fertilizer and irrigation interventions are incorporated as compared to the

Farmers' practice. As a result whole farm net profits increased by almost 25% with only 4% increase in associated integrated intervention costs (Figure 37).

Introducing a better milk yielding cow into the system that produces 10 litres of milk per day have increased the whole-farm net profits to 10% as compared to the Farmers' practice-baseline farming system (Figure 38).

Figure 38: Amravati 2 whole farm scenario analysis



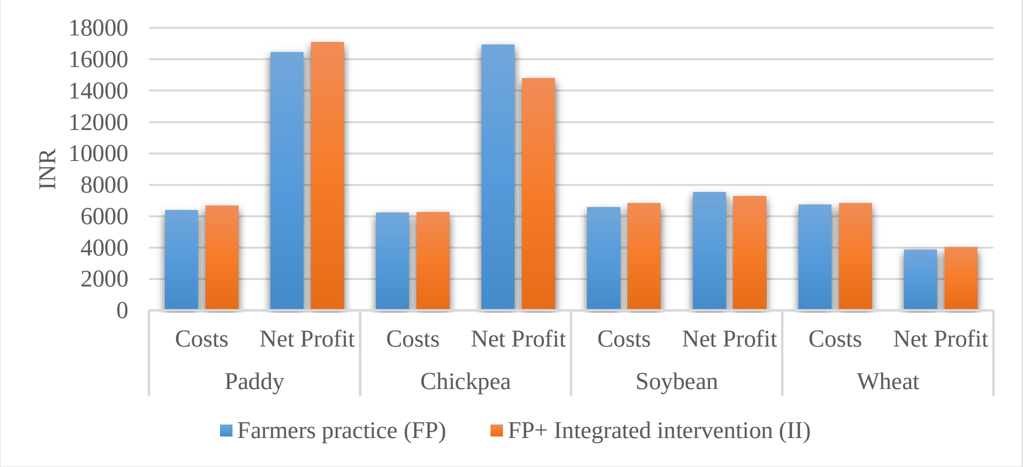
Dhule

Farming System -1

This farming system with an average land size of 1.27 ha is characterized predominantly by grain-legume crop systems like Kharif Paddy followed by Rabi Chickpea and Kharif Soybean followed by Rabi Wheat. Households in this system also hold diverse livestock, including better yielding buffaloes, very low yielding cows and a few goats.

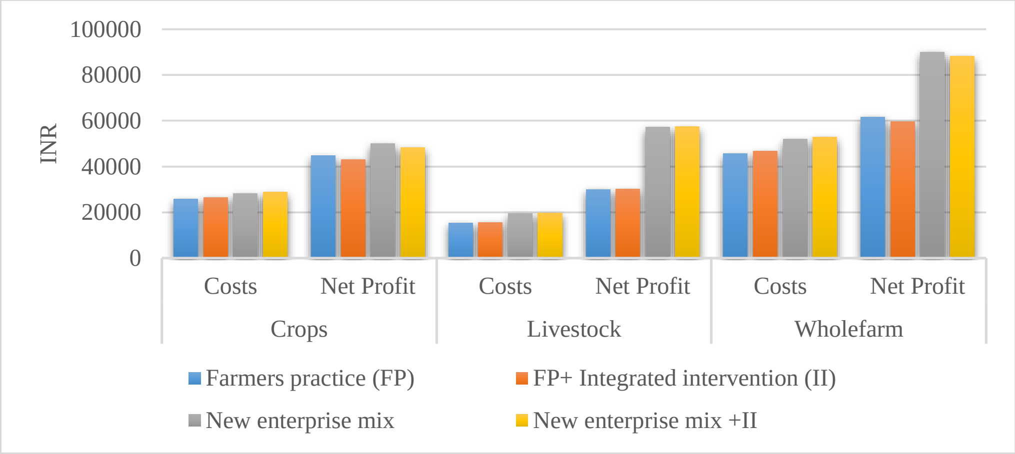
Integrated interventions in this farming system have resulted in an increase of net profits by 3.5% in both Paddy and Wheat with a significant negative returns in Chickpea and Soybean, thus reducing the overall whole-farm net profit by 3% (Figure-39).

Figure 39: Dhule 1 cropping systems scenario analysis



In an alternative scenario we explore the possibility of introducing a perennial tree component (mango) into the system along with livestock intensification by introducing 10 goats into the system as against 3 goats in the Farmers' practice. Doing this has increased the whole-farm net profits by almost 32% (Figure-40).

Figure 40: Dhule 1 Whole farm Scenario Analysis

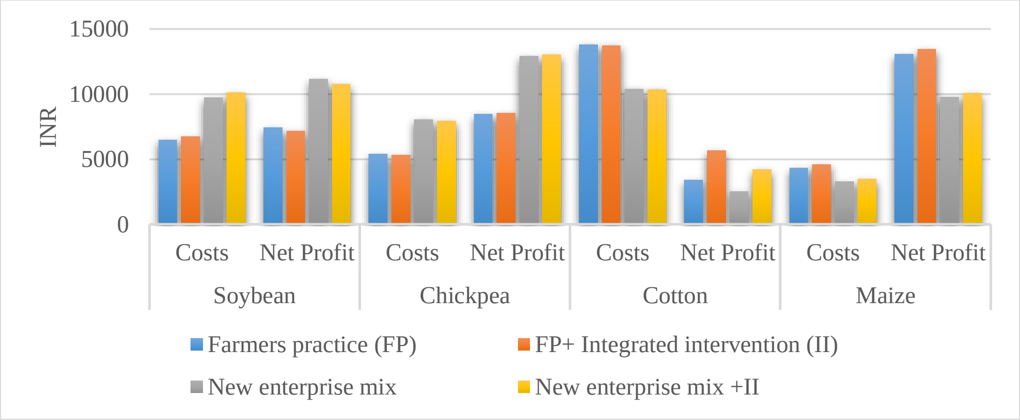


Farming System - 2

Crop production in this farming system consists of Kharif Soybean followed by Rabi chickpea, with some area allocated to Kharif Maize and Kharif Cotton crops in an average total area of 1.27ha. Similar to system 1 they have better yielding buffaloes, very low yielding cows and a few goats.

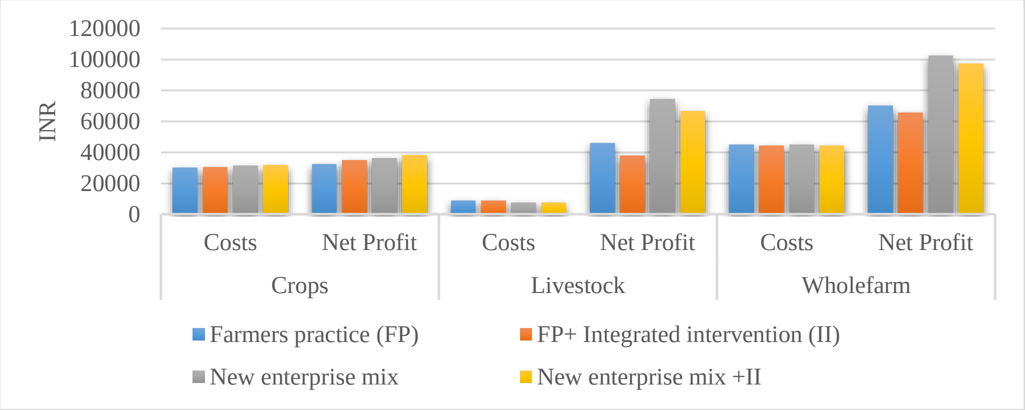
Organic manure, fertilizer and irrigation interventions in the farming system have resulted in an increase of net profits by almost 40% in Kharif Cotton and around 3% in Maize with zero associated cost increase in cotton and 6% increase in costs of Maize. However, the whole-farm net profits have declined by almost 7% due to decreased net returns in Soybean and increased costs in almost all of the crops (Figure 41).

Figure 41: Dhule 2 cropping systems scenario analysis



Removing the low milk yielding cow from the system and intensifying goat production by introducing 10 goats into the system together with increasing the area under Kharif Soybean followed by Rabi Chickpea and reducing the area under both Maize and Cotton as an alternative possibility has increased the whole-farm net profits by almost 33% as compared to the Farmers' practice (Figure 42).

Figure 42: Dhule2 whole farm scenario analysis



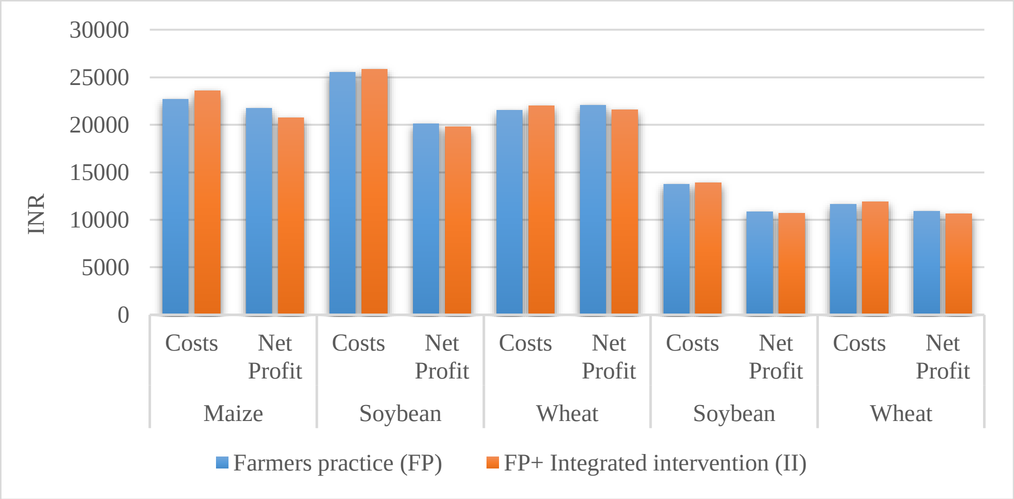
Jalna

Farming System -1

This farming system with an average land size of 2.78ha consists of Kharif Soybean and Rabi Wheat along with Sole Maize Crop in the Kharif season. Households on an average own a cow, buffalo and a goat.

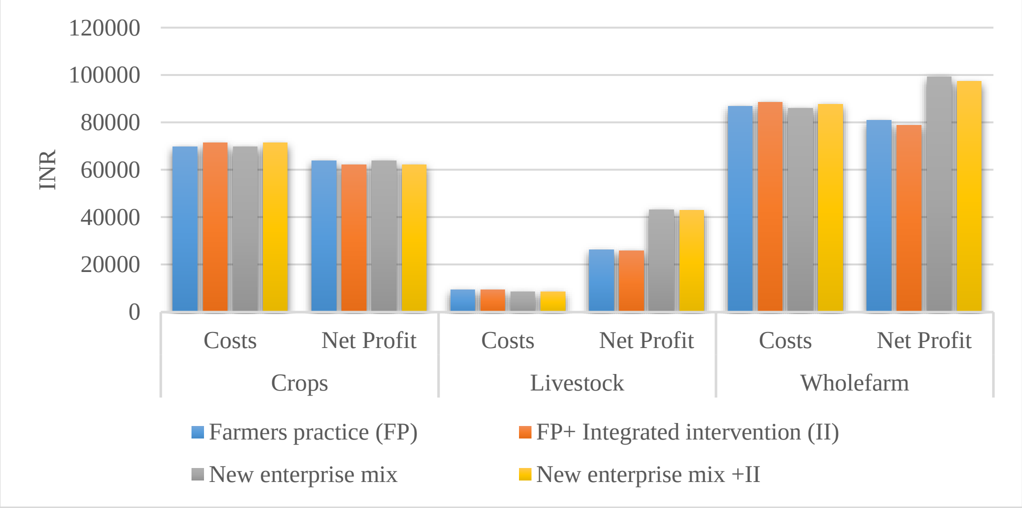
Integrated interventions in this farming system in all of the crops generate negative net returns as compared to that of the Farmers' practice, thus decreasing whole-farm net profits by almost 3% (Figure 43).

Figure 43: Jalna 1 cropping systems scenario analysis



In a different scenario we explore the whole-farm trade-offs of high intensity livestock farming by introducing 10 goats into the system. This has increased the net profit of the system to 19% from that of the Farmers' practice (baseline farming system) (Figure 44).

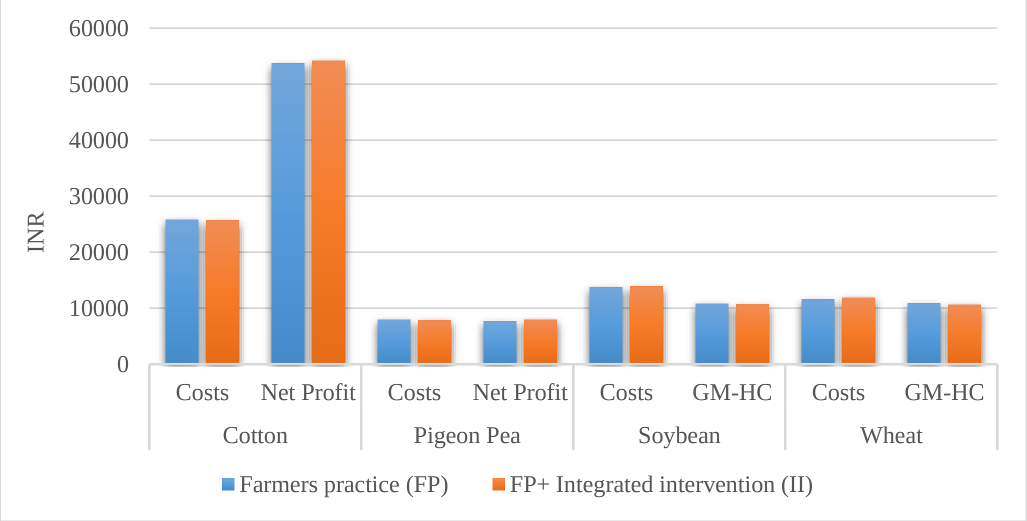
Figure 44: Jalna 1 whole farm scenario analysis



Farming System -2

With a total land size of 2.78 ha households in the farming system cultivate Kharif Soybean followed by Rabi Wheat along with Kharif Cotton with Pigeonpea as an intercrop. They also cultivate Pomegranate which is a perennial component of the farming system. Households in this system also have a diverse livestock that includes cows, buffaloes, and goat (Figure 45).

Figure 45: Jalna 2 cropping systems scenario analysis



Integrated interventions in this farming system generate negligible net returns as compared to the Farmers' practice, mostly because a significant portion of their income comes from the perennial component of the system.

Yavatmal

Farming System -1

With the largest average land holding size of 3.5 ha among the five districts in the study, the predominant cropping system in Yavatmal district consists of Kharif Soybean and Rabi Chickpea, Kharif Cotton with Pigeon Pea as an intercrop and Kharif Sorghum. Households in this farming system own low yielding cows and a few goats.

Organic manure, fertilizer and irrigation interventions into the farming system have resulted in a 55% increase in net returns for Sorghum with an increase in cost of associated integrated interventions by 14%. Significant increase in costs can also be noticed in Cotton, Pigeon Pea, and Soybean with a decrease in net returns as compared to the Farmers' practice. However, overall whole-farm net profits only increase by 4% (Figure 46).

Figure 46: Yavatmal 1 cropping systems scenario analysis

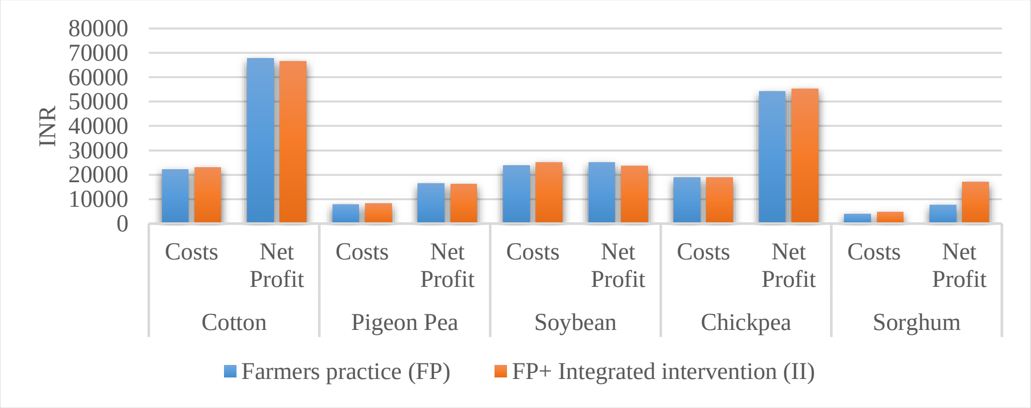
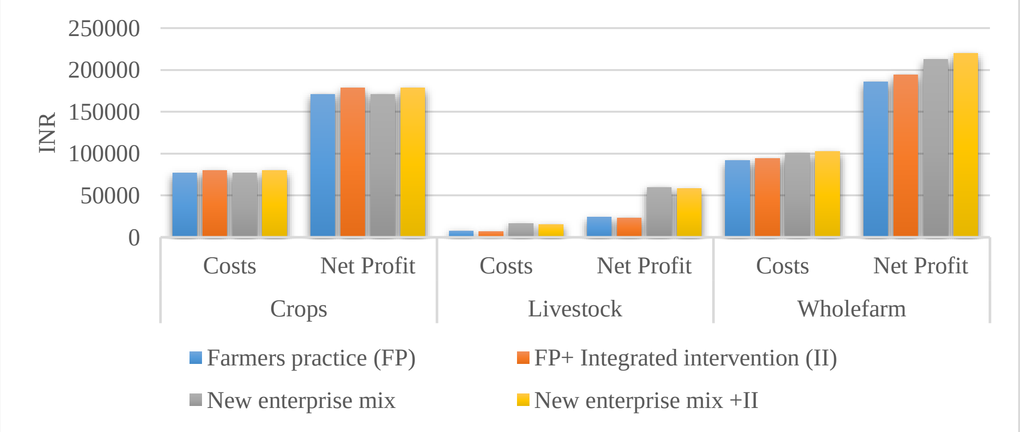


Figure 47: Yavatmal1 whole farm scenario analysis



In an alternative scenario we introduce better yielding cows into the farming system which can be sustained by the availability of good quality fodder within the system. This delivers a 12% increase in whole-farm net profits from that of the Farmers' practice (baseline farming system) (Figure 47).

Farming System -2

The major crops cultivated in this farming system on an average land size of 3.5ha are Kharif Sorghum followed by Rabi Wheat and Kharif Cotton with Pigeon Pea as an intercrop. Households in this farming system have low yielding cows and a few goats.

Integrated interventions in Sorghum and Wheat have increased the net profits by 40% and 100% with the associated costs being increased only by 15% and 8% respectively. Net returns of Cotton crop have also increased by around 12% with the overall whole-farm net profits surging 30% higher than that of the Farmers' practice (Figure 48).

Figure 48: Yavatmal 2 cropping systems scenario analysis

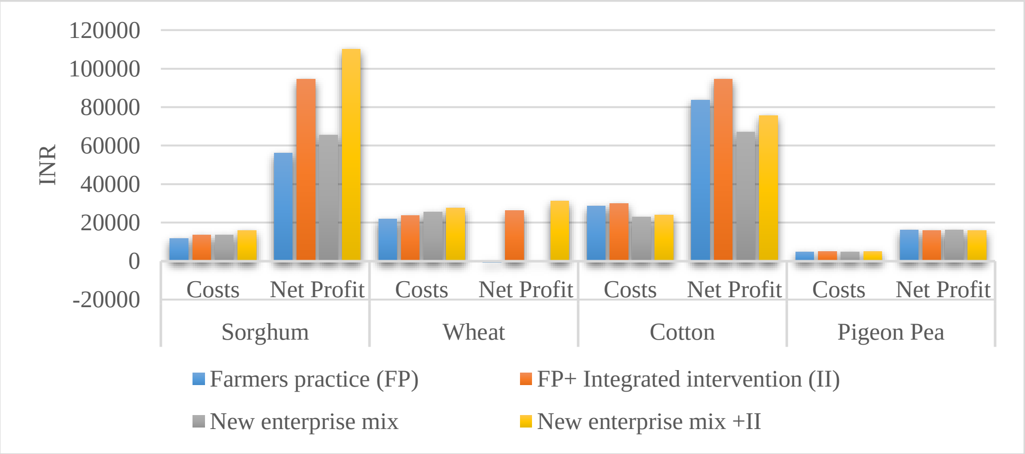
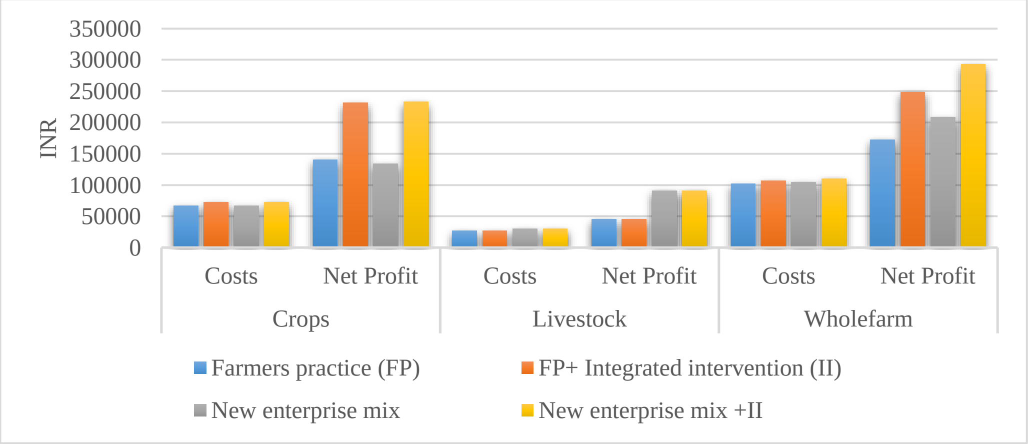


Figure 49: Yavatmal 2 whole farm scenario analysis



Availability of high quality fodder enables us to introduce better yielding cows into the system. In an alternative scenario we also increase the area under Sorghum-Wheat crop system and reduce the area under Cotton. Net profits increase by 17% as compared to the Farmers' practice with almost negligible associated costs (Figure 49).

Discussion

The cropping system model-APSIM simulations demonstrated positive influence of integrated fertility management interventions on ecosystems services (ESS) such as carbon build up, nitrogen leaching and soil moisture. Our whole-farm stochastic modelling approach allowed us to analyze trade-offs and outcomes associated with potential farm systems change on simulated farms with varied cropping systems in each of the five selected districts. The household modelling analysis for farming systems in different clusters provides us contrasting outcomes especially for impact of fertilizer + manure interventions on cropping systems in terms of farm household's cash flows.

With proposed integrated interventions in some cases for example in Ahmednagar for cropping system-1 the first crop green gram (kharif) had significant increase in returns but the returns in next crop (rabi sorghum) decreased via reduced grain yield and biomass for livestock. Consequently the benefits considering the cropping as well farming system were only marginal. The fertilizer + manure which was the major intervention across five clusters provided significant financial benefits in cereals based cropping systems in high potential areas having higher rainfall and better soils in Yavatmal, Amravati and Dhule. For remaining clusters and legume based cropping systems the fertilizer+ manure intervention does not add much to the whole farm profit. Lifesaving irrigation through harvested rainwater in fellow-rabi sorghum in Ahmednagar enhances whole farm profit significantly, but it does not provide significant benefits in other clusters for the existing cropping systems. Considering the family labour (women) availability and own fodder sources the livestock intensification was profitable in Amaravati, Yavatmal and Dhule via higher yielding cows and in Jalna via goats. We have observed a preference for family farms not to desire increasing livestock numbers as it requires too much scarce labour; thus, improving the productivity of current livestock holdings was an option we examined. The forage intensification by integrating sorghum in Yavatmall and Amravati thus lifts profits because it allows higher yielding cows in the system and reduces supplementary feeding costs; a finding also concluded by Finlayson et al. (2012) and Fariña et al. (2013). The greater integration of livestock would also enhance the farming systems resilience. The benefits from forage intensification were greater in the higher rainfall location. As chosen by farm households the integration of perennials mango in Jalna and pomegranate in Dhule are good for whole farm's profit and good for carbon sequestration.

Labour-use efficiency may be one of the key factors in explaining why seemingly more profitable systems are not readily adopted as there was a trade-off between labour-used efficiency and profit. In our study labour-use efficiency fell in almost all scenarios because of diminishing returns to labour inputs. Though the profit per farm household increased in most cases but the extra labour used for agricultural activities under changed systems did not have commensurate financial return for each additional labour over and above the baseline cropping system (Farmers' practice). Affholder et al. (2010) report similar experiences from a simulation model analysis; systems change related to mulching and planting cover crops can improve yields but the extra labour demands result in labour-use efficiency falling. These tensions need consideration when evaluating alternative systems, especially when viable off-farm employment opportunities exist. In the study region, off-farm employment opportunities particularly in Ahmednagar and Amravati exist and are increasing in scope. Labour intensity and the opportunity costs of labour can have profound influence on the adoption of different systems both in developing-country (Lee, 2005) and developed country (Komarek et al., 2012) contexts.

On our simulated farms we addressed the social (labour) and economic (profit) effects of soil fertility enhancing interventions while intensifying crop production. This study highlights the potential of soil fertility interventions and incorporating cereals crops generating forage residues as well short duration legume green gram into current mixed cropping systems on our simulated farms in Maharashtra to increase farm profits. Family labour availability was the key driver for integrating higher yielding livestock and locally suited fruit trees in some of the clusters/farming systems. We may compromise between labour use and profit with reduced labour-use efficiency because cropping/farming system intensification increased the labour demand. Farming systems change will relate to the complex interaction of the above factors and this analysis demonstrated some of the trade-offs and aspects that should be considered when evaluating potential systems interventions. Labour use efficiency may be a key element to explaining the limited uptake of seemingly profitable farm activities.

We advocate research and development actors to focus on the mechanisms behind farming systems changes. At a conceptual level the same mechanisms are operating related to soil water and nutrient processes, livestock feed and growth processes, and even if the same crops and livestock being examined. Differences in household, agro-ecological and market factors will determine the magnitude of change (along with unobservable factors). The magnitude of actual changes depends on location and farm-specific factors (for example, rainfall, soil fertility, labour and markets). We support the view of Giller et al. (2011) that research and development actors should pay attention to providing "baskets of options". Finally the facilitated workshops with key stakeholders on participatory modelling-scenario analysis with household cash flows would help develop more resilient farm designs i.e. the mix of enterprises, crop types and farming practices that satisfy best the objectives of profit, sustainability and resilience.

Experimental games as tool to support institutional change related to sustainable agricultural practices

Recognizing the close links between poverty and natural resource degradation, India invested more than US$ 500 million during the 1990s (Farrington et al., 1999) and more than US$ 1 billion the following decade (Deshingkar and Farrington, 2006) in participatory watershed development. Principally designed ‘to reduce soil erosion and to control gully formation’ (Joshi et al., 2004; Joshi et al., 2005), watershed development programs typically include a complex set of soil and water linked technologies (SWLT). These technologies range from in situ soil and moisture conservation structures (e.g. contour and graded bunds, continuous contour trenches etc.) in both commonly and privately held lands to relatively large structures (e.g. check dams) for increased groundwater recharge. The term SWLT indicates that technologies are functionally interlinked and lead to multiple benefits (reduced erosion and sedimentation, increased groundwater recharge, improved resource use efficiency etc.) if simultaneously adopted and maintained (Amede et al., 2012).

There is strong evidence that various interventions have the potential to achieve a wide range of societal goals – amongst others soil protection and rehabilitation (Wani et al. 2008; Rockström et al., 2010; Garg et al., 2011; Garg et al., 2012; Singh et al., 2014; Karlberg et al., 2015). However, despite its obvious potentials, many communities fail to sustain the benefits over time as they struggle to cooperate in the joint effort to run and maintain the structures (Wani et al. 2008; Joshi et al., 2005).

Even though watershed projects use participatory approaches, little attention is paid to the capacities of communities to design or change institutions and enforce them to ensure sustainability of infrastructure investments. Once projects are completed it is very common that infrastructure quickly erodes losing its capacity to consistently generate benefits. Many communities accept this situation and wait for new projects to come. Most neglected are runoff controlling contour structures (e.g. contour trenches, contour bunds) which very directly reduce soil erosion, improve soil health and increase soil moisture as well as recharge ground water. The maintenance of these structures is labor intensive due to the continuous need to stabilize them through maintaining vegetation cover and desilting. Local communities and farmers are reluctant to contribute labor to maintain such common infrastructure (Bouma et al., 2007).

Existing watershed management programs and projects address the issue of capacities by training members of the watershed communities and staff of project implementing agencies (PIAs)in organizational and technical skills such as community mobilization, project management, supervision of civil works, water audit and crop planning, maintenance of books and accounts of the watershed association/ committees, water charge estimation and collection charges, as well as the planning and implementation of O & M of irrigation systems. The capacities for participatory development of rules for infrastructure maintenance are, however, commonly ignored.

Agreed community institutions are critical in particular as most SWLT structures are commonly managed and it is difficult to exclude anybody from their benefits. Even though, the entire community benefits from well-functioning infrastructure, there are strong incentives to free ride (Hardin, 1968). Maintaining contour structures on shared field boundaries of two or more farmers is also an important cooperation challenge. Previous studies, amongst others, those conducted by the proposing team, have shown that even a small number of free-riders in a community can quickly undermine overall cooperation (Vollan, 2008; Falk et al., 2012; Hayo and Vollan, 2012; Vollan et al., 2013; Gatiso et al., 2015; Javaid and Falk, 2015; Falk et al., 2016).Typical challenges in this context are unequal distribution of benefits, a lack of enforcement mechanisms, and expectations of external help (Kerr, 2002; Ostrom, 2005; Hope, 2007). Often communities are not even aware that they have the means to address the problem.

Theoretical considerations

Groups who jointly use a common-pool resource such as fishery, pastureland, or irrigation systems often face collective action problems. They may fail to coordinate on the optimal level of extraction and/or fail to decide on the optimal investment level (Ostrom et al., 1994; Janssen et al., 2012; Baerlein et al., 2015).

The use of experiments have been useful in disentangling the relations between behavior and institutions, and contributed to fill the gaps between reality, policy and theory (Cárdenas, 2016). For instance, experiments helped to demystify Hardin's grim claims about the impossibility of collective action and community based management of common-pool resources. They sharpened the consciousness for the impact of nonlinear and contextual linkage between group characteristics and their importance for the prospects for collective action (Poteete et al., 2010). Since the 1960s, an extensive range of framed field experiments study water management (Podimata and Yannopoulos, 2015).These experimental games are generally played with farmers in rural communities and imitate real-life resource challenges. They aim to collect information on how people behave (Ostrom and Gardner (1993), Janssen et al., a (2011a), Janssen et al. (2012), Cardenas et al. (2013)) and increasingly to influence behavioral patterns (Meinzen-Dick et al., 2016).

Our work focuses on the special case of the management of irrigation systems. Irrigation systems are defined by two key-characteristics: they are a common-pool resource and they face power asymmetries. An irrigation system consists of two common pool resources: the infrastructure and the water (Ostrom and Gardner, 1993; Janssen et al., 2012). The management of both resources requires simultaneous collective action (Baland and Platteau, 1996; Janssen et al., 2012). The infrastructure needs to be jointly maintained. The water has to be divided amongst the users (Bravo and Marelli, 2008).

The management of irrigation systems becomes even more complex as they are typically marked by asymmetric or sequential access (Janssen et al., 2011b). Along irrigation channels, head-enders can take larger amounts of water, have better water quality, and can generate externalities such as flows of soil and pollutants that affect tail-enders (Cárdenas et al., 2015). This situation affects the willingness to cooperate in the infrastructure maintenance. Upstream users have stronger incentives to contribute to the maintenance. Nevertheless, head-enders may also need the support of tail-enders to sustain the irrigation system. These dependencies increase the likelihood that head-enders react to the tail-enders needs (Ostrom and Gardner, 1993; Lam and Ostrom, 2010; Cárdenas et al., 2015). When head-enders behave un-cooperatively, the amount of inequality tail-enders are willing to accept influences their further reactions and possible reductions in maintenance contributions (Janssen et al., 2011a; Cárdenas et al., 2015).

During the last decades, a series of experiments were conducted to investigate cooperative behavior under asymmetric access. Rapoport (1997) observed in an experimental study that upstream participants appropriate more and downstream participants anticipate and expect them to do so. This position effect was confirmed by subsequent studies (Budescu et al., 1997; Larrick and Blount, 1997; Budescu and Au, 2002; Janssen et al., 2011b; Baggio et al., 2015; Javaid and Falk, 2015).

These dynamics are important factors in determining the outcome of collective action. The behavior of upstream users is leading. When their behavior is dominated by unfair and excessive appropriation, the overall willingness to contribute to the infrastructure declines. Thus, contributions to the public infrastructure are significantly related to the inequality in earnings from resource appropriation in the previous round. Hence, extraction inequality deteriorates collective action prospects (Janssen et al., 2012; Anderies et al., 2013; Cardenas et al., 2013; Baggio et al., 2015). Janssen et al. (2012) conclude that inequality of access does not necessarily impede cooperation, but it can complicate it. This leads to the conclusion that sustainable irrigation management systems require rules and norms which ensure a fair water distribution.

Studies examining institutional infrastructures, such as rules governing the use of the irrigation system, find that externally imposed rules and regulations have a negative effect on provision and contribution (Otto and Wechsung, 2014; Cárdenas et al., 2015). In the same line of argument, Pham et al. (2014) emphasize that in their experiments across countries self-crafted rules had a more positive effect on group behavior than externally imposed ones.

Studies examining the social infrastructure, find that overall sustainability of CPRs depends among others on shared values and worldviews, and the existing network of social relations (Auer, 2006). This is supported by Ostrom and Ahn (2010), who state that these values are the basis for social order and are the driving force for collective learning. For example, trust has a positive effect on cooperation as highlighted by Cárdenas et al. (2015), Janssen et al. (2012), Baggio et al. (2015) and Baerlein et al. (2015). Ostrom et al. (1994) argue that the asymmetries in irrigation systems can be overcome when farmers become aware of their mutual dependencies. In these cases, they are capable to bargain over rules to jointly manage provision and appropriation.

The awareness of mutual dependencies, rules and norms can be raised by integrating a communication treatment. Communication is a popular treatment in both public good (PG) and common-pool resource (CPR) experiments. Allowing communication increases cooperation in common-pool resource dilemmas (Ostrom and Walker, 1991; Ostrom et al., 1992; Balliet, 2010; Poteete et al., 2010; Janssen et al., 2011b; Otto and Wechsung, 2014; Baerlein et al., 2015). In sum, Janssen et al., a (2011a) state that “communication can lead to improved coordination and efficiency, and higher equality of the earnings. As such, equality of earnings leads to more efficient outcomes.”

There are a number of arguments why communication affects cooperation. With the introduction of face-to-face communication, participants get the chance to discuss and coordinate which strategies may yield the best outcomes and which amount should be invested in the subsequent round (Poteete et al., 2010). The induced communication can internalize norms regarding the importance of keeping promises (Ostrom et al., 1994; Balliet, 2010). Voicing commitment in the communication slots may also develop a sense of camaraderie and strengthen identifying norms and values of the group (Shankar and Pavitt, 2002; Janssen et al., 2014). Also, face-to-face communication may change the way participants perceive other participants and therewith change the actions. For example, if a participant believes that others are reciprocators, he may play cooperatively to induce cooperative behavior (Poteete et al., 2010). Communication also allows to detect whether group members complied with agreements (Poteete et al., 2010).

Methodology

The economic experiments were conducted in a random sample of communities in GIZ project areas in Madhya Pradesh /India. They were carried out in coordination with respective Panchayats and the Watershed committees, as well as the NGO FES. FES provided the local field assistants, who were trained in facilitating the experiment. They explained the rules, conducted test rounds, and lead the participants through the game. As location, public places, such as meeting places or schools were used.

The experiments were designed similar to other Irrigation Games, including the provision and appropriation problem, as well as asymmetric access to the irrigation system. Seven fields were placed successively downstream of the dam. Every field belonged to a farmer, whereas farmer player is closest to the dam, player seven the furthest away.

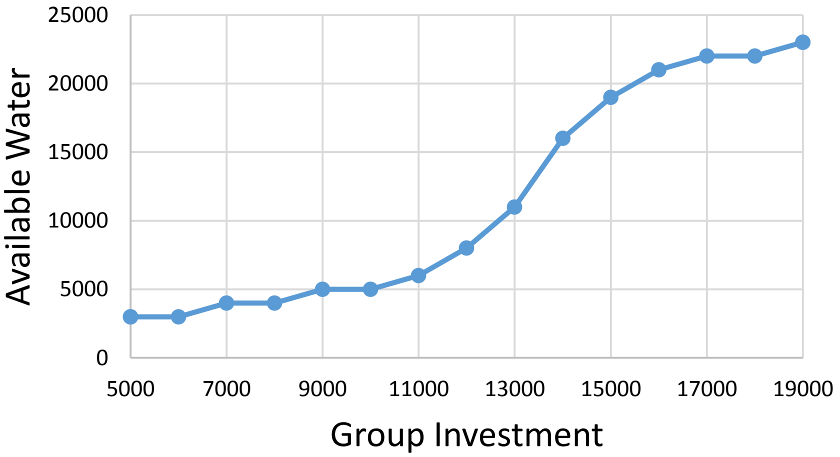
The target group of the experiment are farmers who live close/below a stop dam/water harvesting structure. Amongst these farmers 14 household heads were chosen. Special attention was paid to include women in the games. Overall, 14 people participated in each session as two games were played simultaneously.

The games were structured in two phases. Firstly, five rounds were played with private decisions and without any communication. After playing five baseline rounds with anonymous decisions we introduce social information in terms of revealing the players' decision from round six onwards. To assure that the information of the baseline treatment stayed private, the field positions of the participants were changed. From round 6 onwards, contributions and earnings were written on a table in front of the group. Players could at this stage discuss their experience in the game for five minutes after every round. The discussion was a critical element of the design as it allowed the players to start negotiations and propose rules. One field assistant counted all discussion input by content categories for each participant. A second field assistant summarized the content of the discussions. After the tenth round, a final discussion with the participants and facilitators summed up insights and knowledge participants gained, gave room to discuss the real-live challenges, and how the game may help to optimally tackle these challenges in the future.

At the start of each round, participants were provided with the same initial endowment of 3000 Play Rupees. All participants decided simultaneously on the amount each of them wanted to invest in the maintenance of the dam. The accumulated individual contributions determine the overall available water as a function of diminishing returns (Figure 50).

Everything they did not invested was put aside as savings and later cleared with the yielded returns. To independently make the investment decision participants were given two envelopes: an orange one and a red one. In the orange they found the initial endowment of 3,000 PLAY Rupees, the red envelope was empty. If they wanted to invest money in the dam maintenance, they transferred the chosen amount in the red envelope. Next, the envelopes were handed back to the field assistants, who announced and visualized the overall reach investment level.

Figure 50: The relationship between water availability and investment

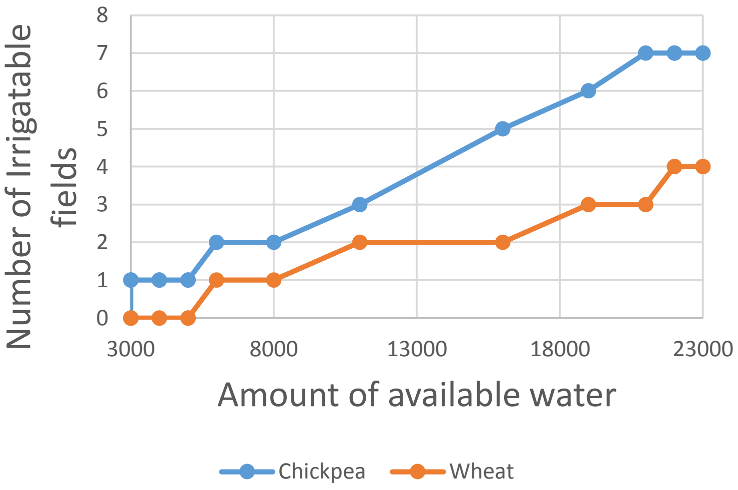


In a second step, participants decided on their preferred crop choice – wheat or gram. Therefore, they used decision cards that were handed over in another envelope to assure anonymity.

Depending on which crop they chose, different amounts of water were used from the dam. Wheat requires more water than gram. The water requirements per one ha wheat is 5500 m^3, and 3000 m^3 for one ha gram. Additionally, the net return of wheat per ha is with INR 15000 higher, than with INR 13000 for gram.

Even under the condition of optimal dam maintenance, there is only enough water to irrigate four fields of wheat, whereas there could be enough water for all seven players to irrigate seven fields of gram (Figure 51).

Figure 51: The Relationship between available water and irrigatable fields (Chickpea/Wheat)



The particularity of this game lies within the relationship of the investments collected for the maintenance, the crop choice, and the sequential access to the water. The socially desirable situation would be if all players invest 2300 Play Rupees and choose gram as crop. However, players have great incentives to deviate from this tactic and choose wheat with the higher net returns. Moreover, the randomly allocated position may influence the decisions.

In the socially optimal case, all seven players invest 2300 Play Rupees, have thus a saving of 700 Play Rupees each, and a net return of 13000 Play Rupees each. This amounts to an earning of 13700 Play Rupees per round.

To gain some additional information, we introduced two payment methods, which were randomly allocated to the villages. 50 percent of the villages received a lump-sum of 2000 INR at the end of the game. The other 50 percent were paid individually. In these cases, the earning per round of a player consisted of the savings and of the net return of the chosen crop. In the end, 1000 Play Rupees were exchanged for 1 real INR. The actual earnings, depended in the end on how each participant played, which position he was on, and how the other participants played.

Additionally, after the game was concluded and participants from villages with individual payment received their reimbursement, we asked these participants whether they would donate a share of their reimbursement for the actual maintenance of the village dam. Therefore, they were asked to select a group member they trust to manage the donated amount in the groups interest. To assure full anonymity within the group but also to ensure that we knew which participant gave how much money, we gave the participants an envelope with their names on. They were asked to privately put as much money into the envelope as they wanted to donate. After we collected all envelopes, the money was counted and publicly handed over to the chosen member.

We included another observation in all treatment villages by asking participants whether they want us to come back with additional game material. To assess this, we asked participants to put a token we handed out into one of two boxes. The boxes were labeled with come back and don't come back. In this case, anonymity was kept by setting up the boxes in a side room. The participants were then asked to one after another to make their choice.

Results

Village key informants of two third of the sites perceived their dam to be in bad condition. Half of them reported some maintenance activities over the last year. Nevertheless, the maintenance activities are seemingly not effective. Figure 52 shows that 76.5 percent of the maintained dams were still in a bad condition. Only a quarter of the dams were in a good state after maintenance works have been conducted. Surprisingly, the not maintained dams were more likely in a better state.

Figure 52: State of the dam depending on its maintenance over last 12 month, (N=42)

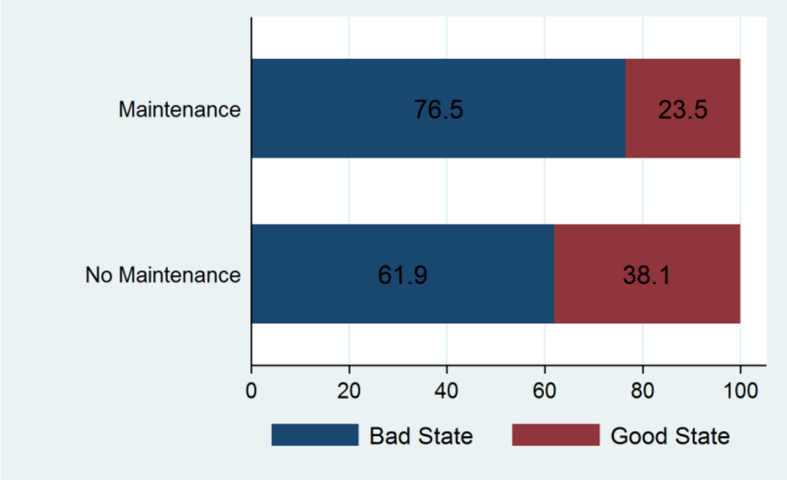
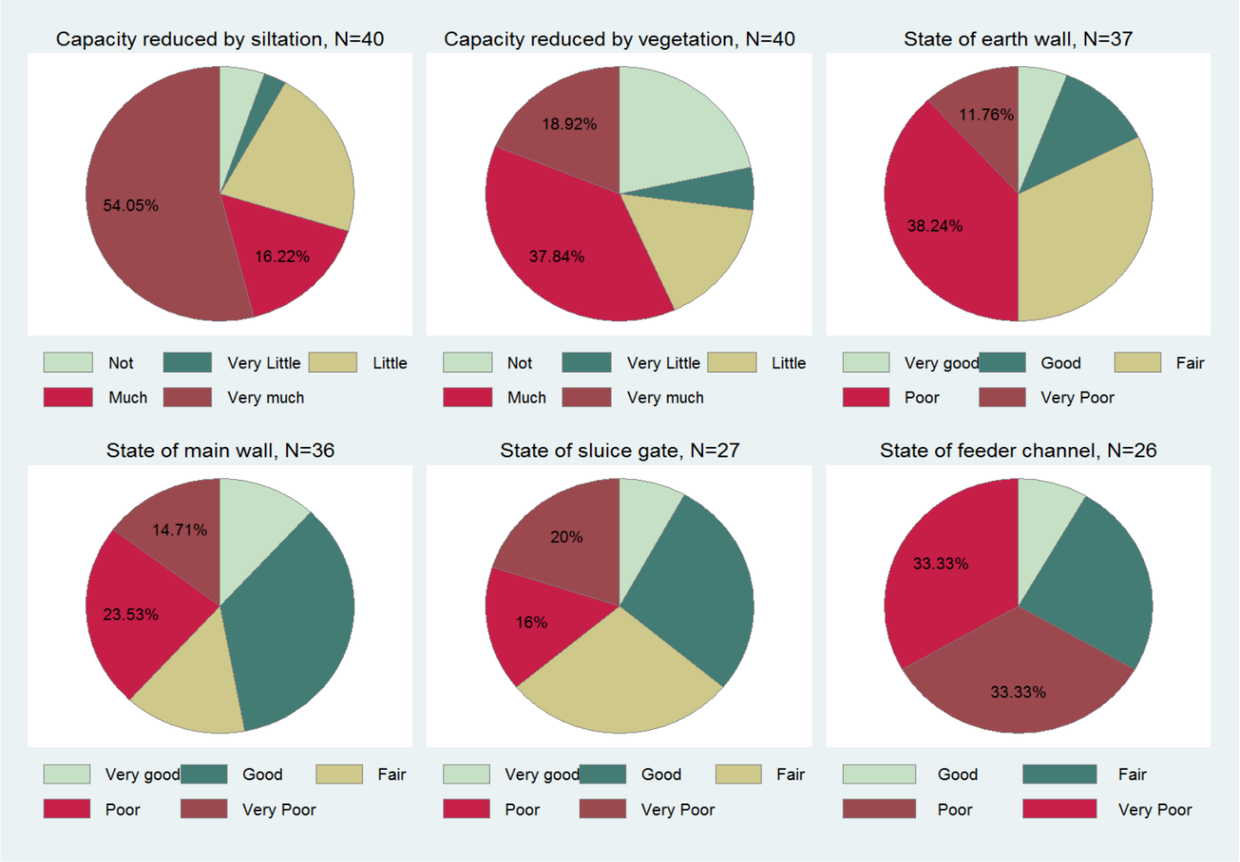


Figure 53: Expert rating of the condition of dams



The descriptive analysis of the conducted baseline survey revealed a rather poor condition of the dams (Figure 53). The NGO experts ranked more than three Fourth of the dams as having lost much or very much of its capacity due to siltation. 57 percent of dams were reported to have a strong capacity reduction due to overgrowing vegetation. In the cases of half of the dams the earth walls were poor to very poor. The state of the main walls was slightly better. Approximately one Third of the sluice gates were rated to be in poor or very poor condition. Two Third of the feeder channels were also rated poor or worse.

Figure 54: Labor contribution based on the state of the dam, N=840

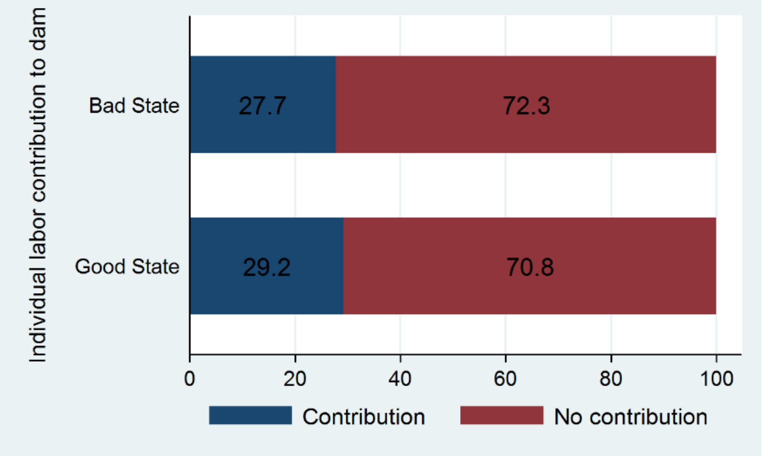


Figure 54 illustrate the individual contributions of the experiment participants to the dam maintenance over the previous year. We distinguish between monetary and labor contributions. Nevertheless, hardly any respondents stated to have paid money for the maintenance. There is no significant difference between dams in good or bad state. Labor contributions are a slightly less common way of contributing to dam maintenance compared to monetary payments. Figure 54 indicates that there is also no distinct difference of contributions between dams of good and bad state.

Figure 55: Labor contributions to the dam based on received water, N=840

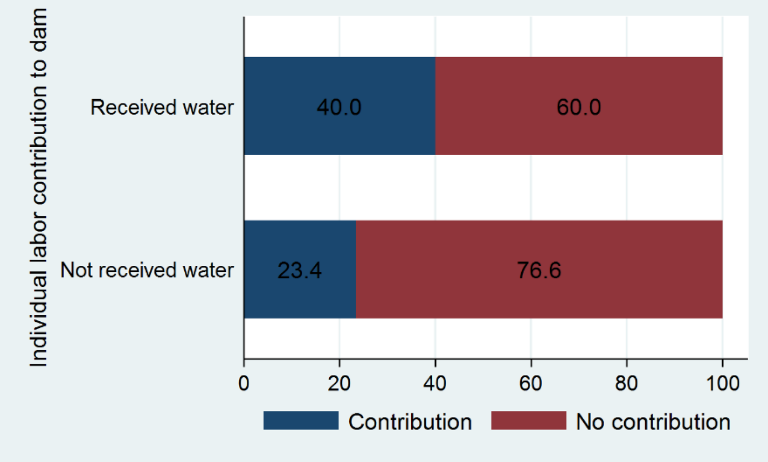


Figure 55 shows that villagers who received water contributed 16 percent more labor compared to those who did not enjoyed it. Money, however, was contributed almost equally, regardless of whether villagers received water from the dam or not.

In the next step we analyze the behavior of our workshop participants in the game. Figures 56 and 57 show that individual investments increase in the communication phase compared to the baseline phase.

Figure 56: Individual investments in maintenance of virtual dam during game by game phases, N= 8,358

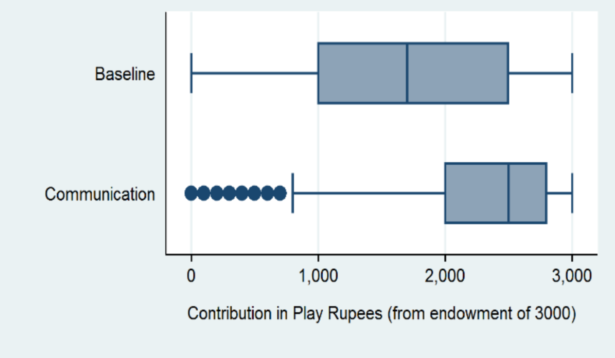
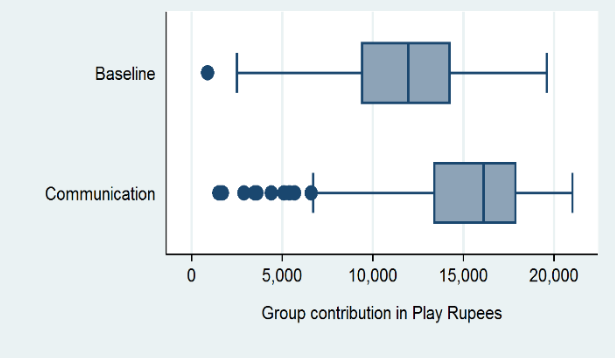
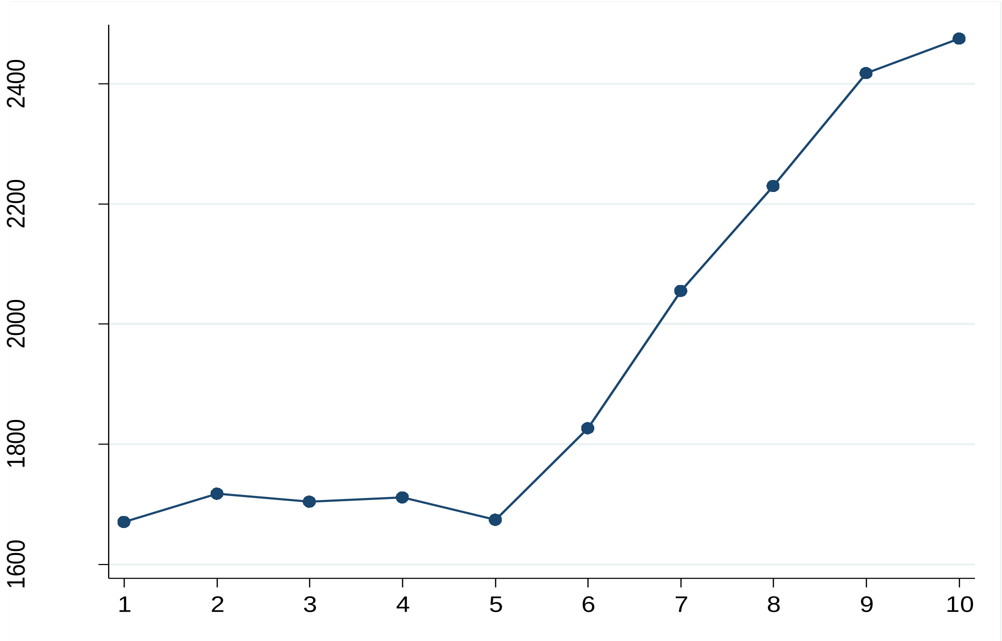


Figure 57: Group investments in maintenance of virtual dam during game by game phases, N= 1190,



Also Figure 58 shows an increase in investments after the player decisions are made public and players could interact in discussions. I also shows that there is little change in investments over the first five rounds with anonymous and discrete decisions.

Figure 58: Average Investment over Rounds in Play Rupees



Also crop choices are positively influenced by the introduction of communication. Figure 59 indicates that in the baseline phase, roughly in 25% of the decisions wheat was chosen. With communication and revealed social information, this share decreases to roughly 15%.

Figure 59: Individual crop choices by game phases, N= 7,726

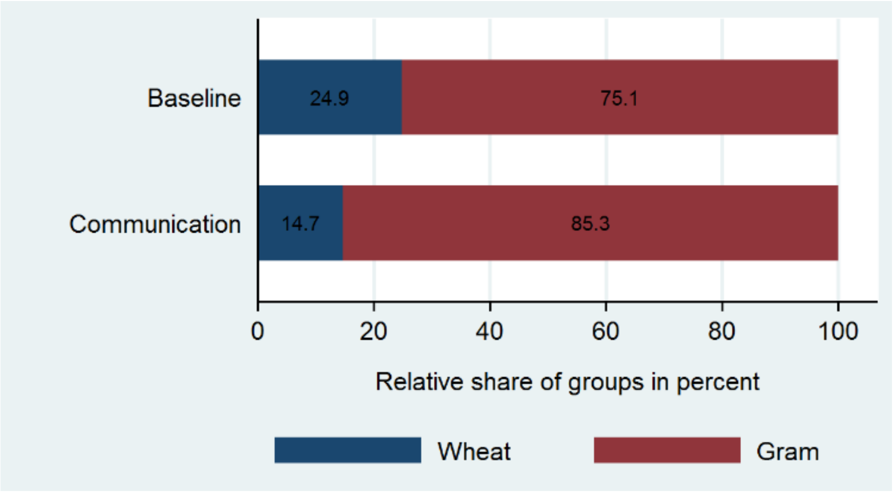
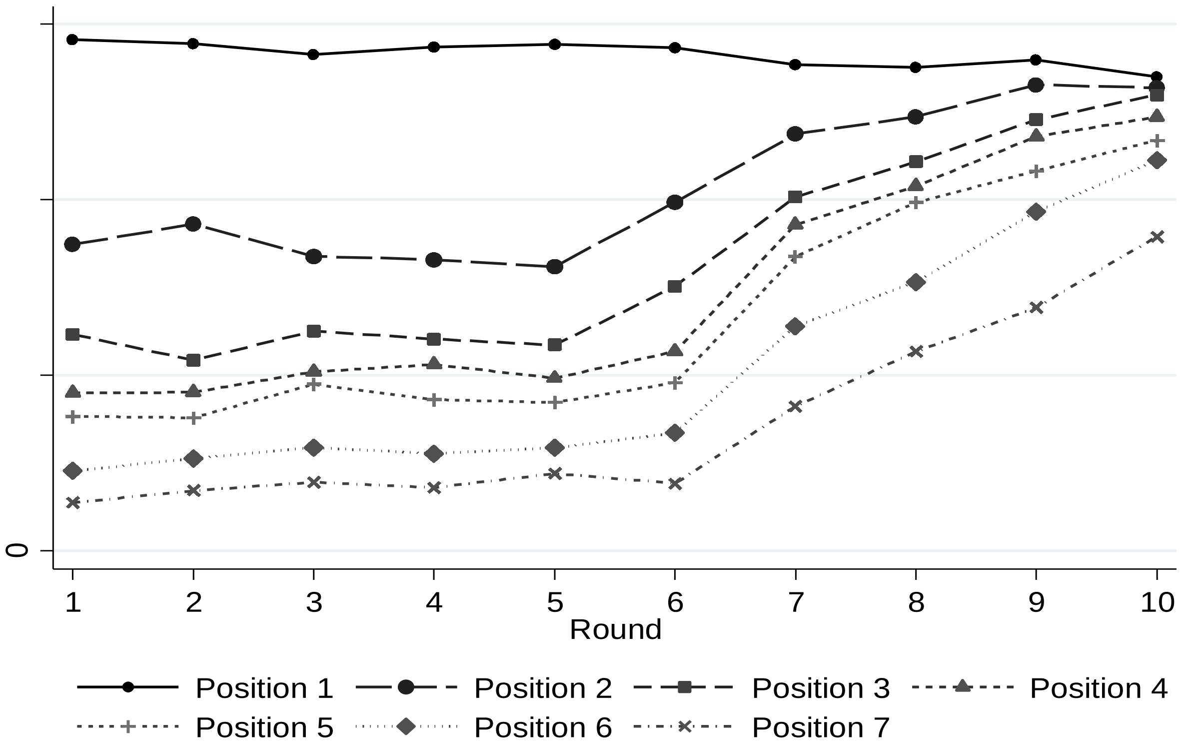


Figure 57 already indicated that even when communication was allowed, in close to 50 percent of the played rounds the investment was insufficient to produce enough water for all group members to grow crops. This is also reflected in Figure 60 showing the individual game earnings by player position. Determined by the sequential water access rule in our game design, the tail-enders have on average the lowest earnings and are the slowest to increase their earnings. Already during the first phase of the game, players in postion one receive water in about 98% of the rounds. In contrast, participants at position seven only receive water in about 3% of the rounds. After the players could discuss, the overall share of players which receive water rises for each position. At the same time, the differences between positions are attenuated. Nevertheless, also with communication, at position one, participants receive about 36% more often water than participants at position seven. This leads to major inequalities between players. In the baseline phase, position one players earn on average 87% more than position seven players. In the communication phase, position one players earn on average 61% more than position seven players. Figure 60 confirms again that the situation is relatively stable during the rounds with discrete and anonymous decisions. Significant learning can be observed only after communication is allowed.

Figure 60: Average Round Earning over Position and Rounds in Play Rupees



Given the complexity of our game we analyze the game dynamics in a next step using regression techniques. First we analyze the baseline rounds. They are the most controlled parts of the experiment, without communication or social information influencing the game dynamics. Thus, models (1), (2), (7), and (8) most strongly reflect the intrinsic cooperation patterns. Table 27 describes the individual investment decision in rounds one to five. Neither game nor socio-economic variables influence the investment decisions in the anonymous rounds. Nevertheless, there is a strong path dependency with this round's investment amounts being similar to last round's investments. The Random effects parameters are significant, which indicate that there is a strong variance between the sites and the individuals which is not explained by the socio-economic variables.

Table 27: Mixed-Effects Regressions Explaining Individual Investment Decisions in Rounds 1-5; Standard errors in parentheses; t statistics in parentheses * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

	(1) Rounds 1-5		(2) Rounds 1-5	
Game Variables				
Position	-8.495	(1.15)	-6.975	(0.99)
Payment	-2.293	(-0.03)	-1.418	(-0.04
Round	-18.77	(-1.44)	-20.66	(-1.56)
Socio-Economic Variables				
Age			0.435	(0.24)
Education			-60.00	(-1.91)
Sex			-87.97	(-1.80)
Community Role			-27.25	(-0.64)
Help			-13.81	(-0.98)
FES Village			45.17	(0.48)
Labor Contribution			11.61	(0.21)
Distance Dam/Field			0.200	(0.07)
Received Water			-78.97	(-1.54)
Lag Variables				
Investment (t-1)	0.318^{***}	(12.46)	0.321^{***}	(13.77)
Avg. Inv. Others (t-1)	0.0491	(0.10)	0.0457	(0.98)
Other Gr. Inv. (t-1)	-0.00886	(-1.56)	-0.00979	(-1.55)
Crop Choice (t-1)	-32.43	(-1.01)	-22.09	(-0.72)
Constant	1295.4^{***}	(10.21)	1502.5^{***}	(8.88)
Site Random-effects Parameters	5.599^{***}	(28.11)	5.620^{***}	(28.14)
Individual Random-effects Parameters	5.683^{***}	(20.80)	5.639^{***}	(20.65)
Residual Random-effects Parameters	6.542^{***}	(138.88)	6.541^{***}	(143.53)
Observations	3131		3063	

Table 28 shows logistic random effects regressions explaining the individual crop choices in the five baseline rounds. The analysis reveals that participants who invest more are more frequently choosing the water intensive crop. We identify a non-linear relation between the crop choice probability and age (Figure 61). Very young and very old players most likely chose the water intensive crop. Players in the early 20s most often played cooperatively. Surprisingly, participants who live in villages where the NGO FES is implementing projects have a higher preference for the water use intensive crop.

Figure 61: Graphical Representation of the Age Transformation in Model (8)

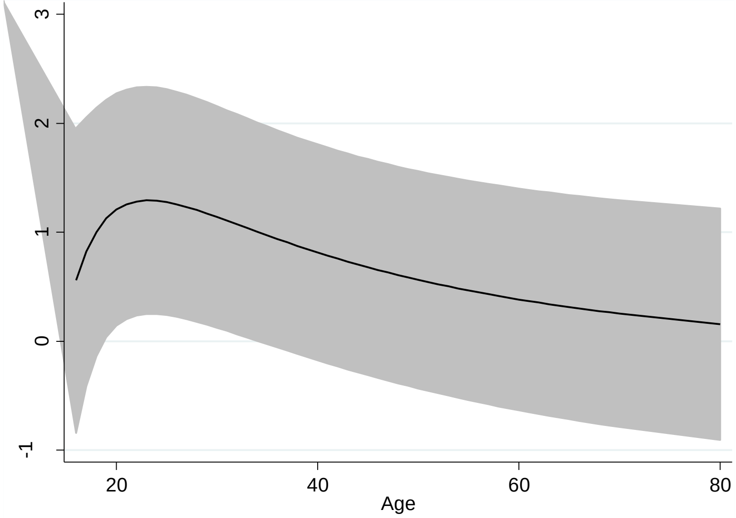


Table 28: Logistic Random Effects Regression Explaining Individual Crop Choices in Rounds 1-5; Standard errors in parentheses; t statistics in parentheses * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

	(7) Rounds 1-5		**(8) Rounds 1-5**	
Game Variables				
Investment	-0.000175*	(-2.56)	-0.000181*	(-2.59)
Position	0.0109	(0.31)	0.00416	(0.12)
Payment	-0.314*	(-2.25)	-0.325*	(-2.21)
Round	0.00122	(0.28)	0.00845	(0.19)
Socio-Economic Variables				
1/Age^2			-4561.0*	(-2.47)
1/Age^2 Log			1725.5**	(2.59)
Education			0.134	(1.13)
Sex			0.254	(1.42)
Community Role			0.100	(0.57)
Help			-0.0990	(-1.67)
FES village			-0.511**	(-3.11)
Labor contribution			-0.0743	(-0.44)
Distance Dam/Field			-0.0195	(-1.74)
Received Water			0.0673	(0.33)
Lagged Variables				
Avg. Inv. Others (t-1)	0.000447**	(3.05)	0.000514**	(3.44)
Other Gr. Inv. (t-1)	-0.0000178	(-0.84)	-0.00000215	(-0.10)
Crop Choice (t-1)	0.368*	(2.18)	0.307	(1.83)
Constant	1.110**	(2.85)	-0.313	(-0.50)
Logged Variance of Random Effect	0.635**	(2.94)	0.598**	(2.78)
Observations	3126		3058	

Before round six, the facilitators announced that from now on all decisions will be disclosed to the group and that the groups can discuss after each round. Models 3 and 4 (Table 29), 9 and 10 (Table 30) as well as Figure 60 indicate that this initiates a stepwise learning process where players manage to increase their contributions over the rounds. Also the frequency of choosing the water intensive crop decreases consecutively. In this phase of the game, appear to behave most opportunistic. They invest in tendency less in the dam maintenance and more often chose the water intensive crop. This indicates a learning effect amongst the youngest participants regarding the crop choice compared to the baseline rounds (compare Figures 61 and 62).

Figure 62: Graphical Representation of the Age Transformation in Model (10)

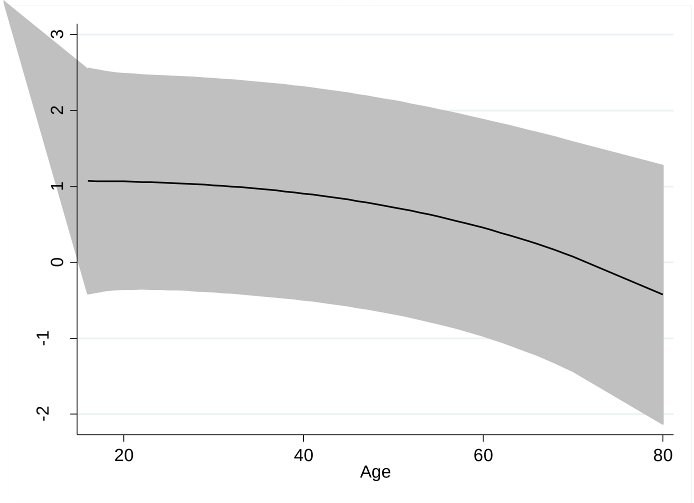
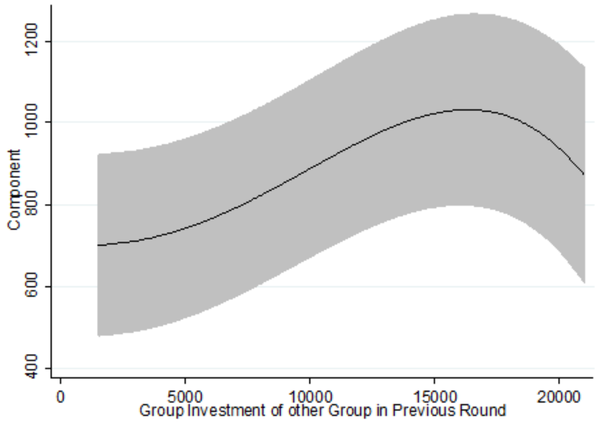


Table 29: Mixed-Effects Regressions Explaining Individual Investment Decisions in Rounds 6-10; Standard errors in parentheses; t statistics in parentheses * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

	(3) Rounds 6-10		(4) Rounds 6-10	
Game Variables				
Position	-7.640	(-1.75)	-7.450	(-1.66)
Payment	-1.418	(-0.04)	-9.755	(-0.24)
Round	97.42***	(6.38)	94.96***	(5.98)
Socio-Economic Variables				
Age			-3.331**	(-2.91)
Education			-4.807	(-0.33)
Sex			-1.775	(-0.08)
Community Role			-3.412	(-0.14)
Help			-6.576	(-0.89)
FES Village			23.93	(0.47)
Labor Contribution			-9.957	(-0.45)
Distance Dam/Field			-0.976	(-0.70)
Received Water			66.66*	(2.43)
Lagged Variables				
Investment (t-1)	0.257***	(12.12)	0.254***	(11.93)
Avg. Inv. Others (t-1)	0.0825	(1.44)	0.0873	(1.50)
Other Gr. Inv.^{3} (t-1)	1.89e-09*	(2.15)	1.88e-09*	(2.12)
Other Gr. Inv.^{3} Log (t-1)	-1.89e-10*	(2.16)	1.89e-10*	(2.12)
Crop Choice (t-1)	63.19*	(2.16)	58.28*	(2.10)
Wheat Others (t-1)	3.425	(0.23)	4.354	(0.28)
Constant	512.9***	(3.64)	639.6***	(4.39)
Site Random-effects Parameters	4.826***	(24.10)	4.787***	(23.68)
Individual Random-effects Parameters	-15.85	(-0.50)	-19.10	(-0.42)
Residual Random-effects Parameters	6.449***	(223.70)	6.446***	(221.02)
Observations	3875		3790	

Figure 63: Graphical Representation of the Other Group Investment Transformation in Model (3) and (4)



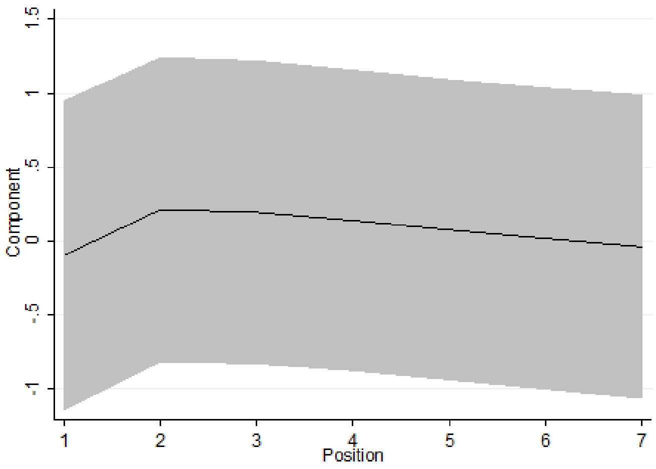
Participants who experienced the benefits of a well-maintained dam in the past by receiving water from it, invest significantly more. There is still a path dependency in the investment decisions. In addition, there is a new strong effect. In the second game phase the players could not only see their own group's decisions. They could also observe the dynamics of the second group. We observe a s-shaped function if the individual investments in relation to the investments of the other group in the previous round (Figure 63). Interestingly, the

Table 30: Logistic Random Effects Regression Explaining Individual Crop Choices in Rounds 6-10; Standard errors in parentheses; t statistics in parentheses * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

	(9) Rounds 6-10		(10) Rounds 6-10	
Game Variables				
Investment	-0.000105	(-1.48)	-0.000110	(-1.51)
1/Position^2	-0.529*	(-2.01)	-0.558*	(-2.12)
Position$^{1/2}$	-0.291	(-1.80)	-0.283	(-1.74)
Payment	0.0276	(0.28)	0.0432	(0.43)
Round	0.113**	(2.71)	0.107*	(2.52)
Socio-Economic Variables				
1/Age^2			-18.77	(-0.21)
Age^3			-0.00000265*	(-2.44)
Education			-0.0200	(-0.25)
Sex			-0.0450	(-0.37)
Community Role			0.131	(1.06)
Help			0.0476	(1.11)
FES village			-0.581***	(-4.83)
Labor contribution			0.261*	(2.17)
Distance Dam/Field			0.00527	(0.65)
Received Water			-0.0190	(-0.14)
Lagged Variables				
Avg. Inv. Others (t-1)	0.000497	(1.90)	0.000577*	(2.18)
Avg. Inv. Others^2 (t-1)	-0.000000111	(-1.59)	-0.000000120	(-1.69)
Other Gr. Inv. (t-1)	-0.0000151	(-0.10)	-0.0000843	(-0.05)
Crop Choice (t-1)	0.880***	(5.44)	0.894***	(5.51)
Wheat Others (t-1)	-0.0666	(-1.69)	-0.0455	(-1.13)
Constant	0.735	(1.36)	1.067	(1.77)
Logged Variance of Random Effect	-1.937	(-1.95)	-2.302	(-1.68)
Observations	3875		3787	

investments of the fellow players in the own group do not influence the decision. In the second game phase we also see an interesting pattern of the player position. Players in position one most probable choose wheat, players in position two most probable choose gram. Then again, the probability to choose wheat slowly increases from position three to seven (Figure 64). Also in the second part of the game, participants who live in villages where the NGO FES is implementing projects have a higher preference for the water use intensive crop.

Figure 64: Graphical Representation of the Position function in Model (9) and (10)



In a last step we analyze all 10 game rounds together. This allows us to differentiate one more feature of our game. Before the 6th round, players were told that from now on everybody will see everybody's decisions and that after each round they could discuss. The first coordinating discussion could, however, only take place after the 6th round. We therefore introduce the variable Disclosure which only expresses whether the players expected that their decisions would made public. The variable Communication expresses whether the players had the chance to discuss amongst each other before the particular round.

The results confirm that announcing the disclosure of social information and making the game more transparent increased investments and reduced the frequency of choosing the water intensive crop. Interesting is that the crop choice changed with the announcement of disclosing the decisions and jumped straight to a new stable equilibrium. In contrast, investment decisions still went up thanks to the possibility to communicate. It appears that for the investment decision both disclosure as well as communication are needed to increase investments and find the social optimum. As the crop choice decision is not as complex as the investment decision, only disclosing social information and building up group pressure seems to be enough to establish a cooperative behavior.

Table 31: Mixed-Effects Regressions Explaining Individual Investment Decisions in Rounds 1-10;
Standard errors in parentheses; t statistics in parentheses * p < 0.05, ** p < 0.01, *** p < 0.001

	(5) Rounds 1-10		**(6) Rounds 1-10**	
Game Variables				
Position^2	-27.65*	(-2.12)	-28.15*	(-2.11)
Payment	-4.791	(-0.19)	-15.76	(-0.57)
Round	6.971	(0.58)	4.214	(0.37)
Disclosure	128.1*	(2.53)	136.8**	(2.63)
Communication	199.0***	(4.07)	197.7***	(3.84)
Socio-Economic Variables				
Age			-21.474	(-1.32)
Education			-30.09	(-1.84)
Sex			-37.35	(-1.58)
Community Role			-10.51	(-0.49)
Help			-9.163	(-1.17)
FES Village			6.989	(0.21)
Labor Contribution			-0.552	(-0.02)
Distance Dam/Field			-0.652	(-0.44)
Received Water			7.353	(0.27)
Lagged Variables				
Investment (t-1)	0.322***	(19.46)	0.324***	(20.53)
Avg. Inv. Others (t-1)	0.118**	(2.78)	0.119**	(2.73)
Other Gr. Inv.^{3} (t-1)	1.73e-09**	(2.78)	1.65e-09**	(2.63)
Other Gr. Inv.^{3} Log (t-1)	-1.71e-10**	(-2.75)	-1.63e-10**	(-2.59)
Crop Choice (t-1)	17.18	(0.68)	16.36	(0.68)
Constant	755.1***	(9.17)	926.1***	(8.63)
Site Random-effects Parameters	4.215***	(11.29)	4.233***	(12.81)
Individual Random-effects Parameters	4.900***	(16.45)	4.850***	(14.59)
Residual Random-effects Parameters	6.535***	(279.20)	6.534***	(278.47)
Observations	7006		6853	

The models explaining the individual investments over all rounds still show the before observed s-shaped function of the investments of the other group. It increases until the other group reaches the socially optimal group investment of 16.000 Play Rupees and falls afterwards. Over all rounds we can also find a positive effect of the investments of the other players in the own group.

Analyzing the crop choice over all rounds still shows a higher frequency of selecting the water use intensive crop in villages where the NGO is implementing projects. The age effect resembles the age effect in model (8) (Table 30). The water use efficient crop is more likely chosen when the investments of others in the previous round are high or when it was already chosen in the previous round.

Table 32: Logistic Random Effects Regression Explaining Individual Crop Choices in Rounds 1-10; Standard errors in parentheses; t statistics in parentheses * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

	(11) Rounds 1-10		**(12) Rounds 1-10**	
Game Variables				
Investment	-0.000145**	(-3.02)	-0.000151**	(-3.12)
Position	0.000967	(0.06)	0.00110	(0.07)
Payment	-0.133	(-1.32)	-0.115	(-1.14)
Round	0.0590	(1.80)	0.0493	(1.48)
Disclosure	0.375**	(2.66)	0.384**	(2.70)
Communication	0.108	(0.75)	0.0985	(0.68)
Socio-Economic Variables				
1/Age^2			-3394.9**	(-2.68)
1/Age^2 Log			1276.6**	(2.80)
Education			0.0470	(0.58)
Sex			0.0964	(0.78)
Community Role			0.135	(1.10)
Help			-0.0162	(-0.40)
FES village			-0.555***	(-4.91)
Labor Contribution			0.104	(0.89)
Distance Dam/Field			-0.00471	(-0.60)
Received Water			0.0194	(0.14)
Lagged Variables				
Avg. Inv. Others (t-1)	0.000244**	(2.87)	0.000285**	(3.32)
Other Gr. Inv. (t-1)	-0.0000124	(-1.02)	-0.0000658	(-0.53)
Crop Choice (t-1)	0.559***	(6.03)	0.555***	(5.94)
Constant	0.811***	(3.68)	-0.0480	(-0.12)
Logged Variance of Random Effect	-0.0186	(-0.13)	-0.126*	(-0.83)
Observations	7001		6848	

Discussion

Standard economic theory predicts a selfish non-cooperative Nash equilibrium strategy of individual players, especially when asymmetric access impedes access to CPR. However, a vast number of public good and CPR experiments has demonstrated positive contributions from the first to the very last round. With no communication or sanction opportunities at hand, the investment level is about 30–40% of the players' endowment experiments (Chaudhuri, 2011; Fehr and Gächter, 2000; Ledyard, 1994). On top of that, most public good games find that investments decrease as the game proceeds (Ledyard, 1995).

Participants in the field experiment in Madhya Pradesh invest more than predicted by the Nash equilibrium in the baseline round: about 56% of their endowment. This is a commonly observed behavior in irrigation experiments (Cárdenas et al., 2011; Janssen et al., 2011b; Javaid and Falk, 2015). Additionally, the results of the Mandla experiments support that players in advantageous upstream positions have significantly higher earnings. However, these inequalities do not affect the investment and appropriation levels as suggested by most other irrigation studies. Ostrom and Gardner (1993) and Janssen et al. (2011b) suggest that upstream-users invest and appropriate significantly more than tail-enders, which is then anticipated by the downstream-users. Additionally, high inequalities in earnings arise due to the asymmetric access (Budescu et al., 1997; Budescu and Au, 2002; Cárdenas and Carpenter, 2008; Janssen et al., 2011b; Javaid and Falk, 2015), which can impede cooperation as downstream players may withdraw their cooperative behavior to punish upstream players (Janssen et al., 2011a).

In the Mandla experiment, investments and crop choices remain constant over the five baseline rounds. However, it can be argued that as the baseline-setting was fully anonymous, participants had not the chance to realize the existing inequalities and thus did not react to them. In the first rounds of the communication phase, inequalities where still immense and observable. But instead of decreasing investment levels, the overall level increased. Similar findings are reported by Javaid and Falk (2015), Janssen et al. (2011a), and Bouma (2007). Against this background, Janssen et al. (2011a) argue that participants accept the asymmetric access due to historical traits. Irrigation systems develop over time and their infrastructure expands to more marginalized regions over time. Thus, head-enders often arrive before tail-enders having the chance to exploit the best land. In systems developed this way, asymmetries are perceived as fair. On the other hand, Javaid and Falk (2015) argue based on Hofstede (2001) that their experiment participants, farmers in Pakistan, might be more tolerant toward inequalities in earnings due to Pakistan's hierarchical society. Those who come from a culture with an inherent hierarchical order are more likely to accept assigned positions without a need of justification. This can also be applied to farmers in India as India is still characterized by its caste system and the hierarchies that emerge from this system.

From round six on, investments strongly increase and more often the socially beneficial crop was chosen. We interpret this as a learning effect. The Round variable is not significant in the first game phase but becomes highly significant in round six to ten models. It appears that the anonymous decision during the baseline rounds did not facilitate much learning. Only by disclosing the players' decisions and allowing communication, the game dynamics change towards stronger cooperation. Additional support for this learning effect can be seen in the age variable. While the behavior of the older participants remains the same over rounds one to five and rounds six to ten, the younger participants become more cooperative in the second game phase. Thus, the combination of the introduction of social information and communication is highly effective in increasing cooperation levels. Social information and communication directly address social norms and shared values. These values and norms are the vehicle for collective learning and the basis for a social order inside a community (Bravo and Marelli, 2008). The learning effect can lead to the establishment of a social norm favoring cooperation. We hope that this experience also encourages more cooperative group behavior in real life. Generally, identifying and sharing social norms and values appears to be highly beneficial for cooperation (Gneezy et al., 2016; Janssen et al., 2014; Javaid and Falk, 2015; Shankar and Pavitt, 2002).

The communication records show that players mainly used the discussion time to coordinate, voice commitment and thereby strengthen norms and values of the group. This is in line with the literature on communication and cooperation. It is frequently argued that communication creates awareness of mutual dependencies, develops a sense of brotherhood, and allows to bargain over rules (Balliet, 2010; Janssen et al., 2011b; Lindahl et al., 2015; Ostrom et al., 1992; Ostrom and Walker, 1991; Otto and Wechsung, 2014; Poteete et al., 2010). Several studies also show increased cooperation when participants expect and/or observe that others cooperate (Fischbacher and Gächter, 2010; Fischbacher et al., 2001; Janssen and Baggio, 2017). Revealing social information enables the players to learn from each other, which again influences the social norms of a participant (Croson and Shang, 2008; Javaid and Falk, 2015). Observability can further induce peer pressure and social sanctions (Mittone and Ploner 2011, Falk et al. 2012).

One factor that is observable across the regression analysis is the effect of the group dynamics, within and between groups. This is in line with various experimental designs which have shown that between-group competition promotes within-group cooperation (Bornstein et al., 2002; Gunnthorsdottir and Rapoport, 2006; Puurtinen and Mappes, 2009; Tan and Bolle, 2007, Hausken 2000, Atran & Henrich 2010, Burton-Chellew et al. 2010). Puurtinen and Mappes (2009) argue that competition between groups affects the perception of group members and thereby feelings in the game. By comparing with the personal level of cooperation against the other groups' behavior, subjects perceive their group members more as collaborators than as competitors. "The within-group social dilemma of the public goods game can be dissolved by between-group competition because between-group competition aligns individual and group interests (West et al., 2007)" (Puurtinen and Mappes, 2009, p. 358).

Implications and conclusions

The main objective of designing and playing this game was to develop the institutional capacity of the players. The received feedback and the content of the discussions encourage us. Players commonly expressed that the game experience made them aware of multiple cooperation challenges in the community. They discussed plans to take the related issues to the next gram panchayat meetings. Whether this will at the end lead to actual behavioral changes still needs to be seen. Our baseline assessment allows us to assess this impact after some time.

Conclusions and policy implications

This report provides results of a 1.5 year study on economics of land degradation. Our group chose a novel approach in applying crop models for estimating how farm management practices affect the provision of diverse ecosystem services. The report demonstrates the rich data collected and estimated with simulation models. Our work helped to raise awareness for the impacts of agricultural practices on non-marketed and difficult to measure ecosystem services.

The overall picture emerging is that the total ecosystem service impacts resulting from alternative on-farm practices are dominated by the net profit. It is the main factor compared to the other ecosystem service goods and bads. The only remarkable additional factor are the hidden water costs. Farmers face operational costs for pumping and applying water to the fields. These costs are included in our profit calculations. They do not pay, however, for the water itself. Mainly due to differences in water consumptions, we can find examples where management practices are more favorable in terms of profits but provide lower total ecosystem service values compared to other practices. There is a high likelihood that such constellations lead to decisions which are not optimal in terms of social welfare. The profit is fully enjoyed by the farmers while the hidden water costs are spread amongst a larger number of people from the local to the regional scale. As a result the incentives from the profit are most strongly driving the farmer's decisions while the water ones are rather neglected. Our perception assessment confirms that farmers are little aware of hidden impacts of their action on public goods or common pool resources.

Famers and extension officers often state that water is the most critical constraint for agriculture. If this was true, the question emerges why the focus does not shift from land productivity to water productivity. Our simulations show for instance that the sorghum-fallow cropping system promises in most environments poor net profit per ha but highest net profit per water unit evapotranspiration. The system has in particular comparative advantages on poor soils and dry environments where it performs even better than most other cropping systems in terms of profit per ha. Under more favorable agro-ecological conditions cropping systems like cotton, maize-chickpea, soybean-chickpea and rice-chickpea outperform the sorghum-fallow system in terms of profits per ha but not in terms of profit per water unit used. It is not our intention to promote specific cropping systems. We only want to raise awareness on the hidden costs of water use. Especially in areas with strong water scarcity, distributing water over a larger area, growing water use efficient cropping systems which are less profitable per hectare, can increase the overall agricultural production of that area.

Farmers report changes in cropping pattern over the last decade. Many Ahmednagar farmers have shifted from traditional food crops like pearl millet and sorghum to more profitable vegetable crops such as onion. In Amravati and Yavatmal, farmers are cultivating pigeon pea, cotton, or soybean-cotton intercrops. The area under soybean and cotton fluctuates. Farmers cultivate soybean after three to four years of cotton for crop rotation. Our results confirm a reasonable positive value of nitrogen fixation of the legume crops. Farmers with irrigation facility, often choose soybean in kharif and wheat in post rainy season.

The area under finger millet declined in Dhule district due to low yields and was replaced by paddy. For the same reason, the area under the pearl millet crop is reduced in Jalna district. It was according to our respondents largely replaced by cotton and maize. In Madhya Pradesh, the area under millets also declines and is replaced by paddy. In this case more frequent cases of extreme rainfall events and untimely arrival of the monsoon were mentioned as main reasons.

The reported changes in cropping patterns correspond to the picture emerging from our simulations. The replaced systems are less profitable then the newly introduced ones. Nevertheless, especially in areas with critical water scarcity, cotton, paddy or maize systems may not be smart cropping choices on the community level.

Water use efficiency has national and global relevance given that India is one of the world regions with most intense water use. Surface water over-abstraction is projected for large parts of India for the coming decades (Wada & Bierkens 2014). No country is abstracting more nonrenewable water than India (Wada et al. 2012).

Our results confirm the overall positive effect of manure on all observed ecosystem service indicators across different agro-ecological environments, cropping systems and climate scenarios. This is the more remarkable as our models cannot capture all the benefits manure provides to soils and agriculture. It remains, however, a question how so much manure can be made available. Approximately 15 megatons of manure would be required and distributed per year to apply 3 t per ha to the total cropping area of our study region.

Fertilizer and irrigation have more differentiated effects on profits and ESS provision. The effect of irrigation is strongest in dry environments but turns rather negative in wetter areas. It might still improve yields but taking associated costs into account it is often more profitable to reduce irrigation. This effect would even become stronger if the water itself was priced.

The simulations of climate change impacts do not give a consistent picture. In many cases either the hot-dry or the cool-wet climate scenario improves the performance of management packages. In many other cases the scenarios would lead to worse outcomes. It should be kept in mind that both climate scenarios assume an increase in temperature and precipitation – only to a varying degree. Our analyses mainly indicate that climate change will affect the relative attractiveness of cropping systems. This situation will make adaptation strategies of farmers necessary. Our modeling approach offers a tool to identify the best suited systems under changing climate in particular areas. The modelling is a much cheaper option for finding adaptation options than a risky trial and error process.

In general, our approach allows to make predictions based on setting parameters for specific localities. We could estimate the impact of bio-physical factors on ecosystem service provision at much lower costs than would be required in empirical field experiments. In the process of project implementation, different stakeholders expressed the view that our approach can help government and non-government extension services to optimize information dissemination to farmers on returns vs. sustainability. The simulation modeling therefore has the potential to support very location specific management decisions. It was beyond the scope of this project to develop a decision support tool for extension staff and farmers. We will be searching for opportunities to develop such tools in future.

Summary of critical drivers preventing and supporting the adoption of innovative soil management practices

The project conducted a Stakeholders Workshop on Economics of Land Degradation (ELD) in India on the 26th October 2017 at the Grand, Vasant Kunj hotel in New Delhi, India. One important topic of the workshop were the critical drivers preventing and supporting the adoption of innovative soil management practices. Different regional, national and international stakeholders expressed the view that the still most critical constraint is the lack of information. The stakeholders highlighted strong differences in the perception of the value of ELD and Ecosystem Services amongst different implementers at different levels from the individual farmer to policy makers at the international level. But it is not just a matter of disseminating available information and raising awareness. The adoption of innovative agricultural practices is also prevented by the complexity of the system. In a very lengthy process of trial and error, farming communities identified over centuries the best suited farming practices for a particular area. In a more and more rapidly changing world aspirations of farmers shift, input and output market prices become increasingly dynamic, new technologies become available, and the weather patterns start to change. Under such accelerating developments, real life experiments are too slow and costly to provide the information farmers need. Our modelling approach demonstrated a low-cost alternative allowing to estimate the impact different farming options under specific bio-physical conditions.

One critical driver preventing the implementation of more sustainable farming practices is the inability of markets to capture hidden costs, in our case in particular for water. Stakeholders in the aforementioned workshop expressed that the strong focus on profits hinders the transformation towards a more ecosystem service friendly agriculture. Agricultural profits steer farmers in some cases into choices which are not optimal in terms of total ecosystem service provision. Hidden costs are often not experienced by the individual farmer. If one farmer take as much water as is required to grow more profitable but less water use efficient crops than overall social welfare may be negatively affected. Government interventions reducing the costs of pumping and applying water even increase such market inefficiencies. For instance, energy subsidies ease the lifting of ground water and some minimal support prices encourage water inefficient crops. Such subsidies are an attractive instrument to improve poor smallholders' productivity and increase political popularity amongst farmers. Long term implications are largely ignored by both the groups. This underpins the aforementioned need to raise awareness on unintended consequences at different scales and better target the support given to farmers. The stakeholders in the aforementioned workshop confirmed the potential of our modelling approach to support decision on incentive schemes and their implementation.

Strongly linked to the implementation of sustainable farming practices is the management of water and water infrastructure. Incentives to free ride on the efforts of others to maintain community dams and channels is a key driver preventing sustainable water harvesting. Another problem are possibilities to appropriate larger amounts of water in order to grow water use inefficient crops instead of sharing water amongst a larger group of people for growing water use efficient crops. Both challenges can partially be solved on the local level through better governance. For this to happen an increased institutional capacity of famers is needed. In addition, it should be acknowledged that there are benefits from sustainable water and water infrastructure management beyond the local scale. The inefficient use of water has the potential to cause major tensions in the country. This can even economically justify subsidies which provide incentives for ecosystem smart land management or for maintaining minor irrigation infrastructure.

Our household models point at another critical constraint. The integrated crop–livestock-household analysis indicates that family labor availability is the key driver for integrating farm activities into a particular farming systems. In some cases, labor constrains the possibility to intensify farming systems which are better in terms of profit as well as ecosystem service provision. Labor use efficiency is likely to be a key factor explaining the limited uptake of seemingly profitable farm activities. At a conceptual level the same mechanisms are operating related to soil water and nutrient processes, livestock feed and growth processes, and even if the same crops and livestock being examined. Differences in household, agro-ecological and market factors will determine the magnitude of change.

Inconsistent sectoral policies are another challenge preventing the adoption of innovative soil management practices. Policies on improving agricultural productivity, increasing water use efficiency and decreasing pollution and GHG emissions need to be harmonized on the state and central government level.

Proposal on how stronger incentives can be created for the adoption of the innovative soil management practices

As mentioned before, on the local level stronger incentives are needed to manage soils, water and water infrastructure in more sustainable ways. While watershed projects strongly invest in technical interventions, the institutional capacity of communities remains weak. Institutional capacity development needs to go beyond the training of bookkeeping, accounting and facilitation skills. Communities need to be empowered to develop and enforce rules which are accepted by their members and adapted to their local conditions. Our game based capacity development approach can be one useful tool in this process. The main objective of designing and playing the game was to develop the institutional capacity of the players. The received feedback and the content of the discussions encourage us. Players commonly expressed that the game experience made them aware of multiple cooperation challenges in the community.

We also stressed before that in particular hidden water costs are the most critical ecosystem service apart from profits. Water costs/prices are a standard instrument to motivate farmers to cultivate more water use efficient crops and use water saving irrigation technologies (Ray 2007). India has a history of using diverse water pricing mechanisms. This includes pricing mechanisms based on the method of irrigation, charges by crop and season or volumetric charges (Tsur & Dinar 1997). There are reports about emerging rural water markets in India (Saleth 1998). It can, however, be asked whether these are really water markets or rather markets for providing transportation services of water. The farmer who is lifting the water is not paying for the water but only has the investment and operational costs of storing and moving the water. We acknowledge that in the process of moving the water a privatization of the water takes places and eventually water is sold on the basis of demand and supply. The informal local markets for water supply are little transparent. Our explorative assessments showed diverse payment practices. We found examples for payments per irrigation event ranging from INR 1200 to 2500 per hectare. Another payment system is to give the water supplier one Quarter of the harvest. Yet another system is the provision of labor to the water supplier. The exemplary evidence suggests water price ranges between 2.5 and 5 INR/m³ which we believe is consistent with the value set on the basis of water facility prices. Even if these prices are not paid for the water itself, they indicate a remarkable willingness to pay for water.

The most direct way of encouraging more efficient use of water would be to cut subsidies on electricity. Kumar (2005) showed that unit pricing of electricity influences groundwater use efficiency and productivity positively. It also shows that the levels of pricing at which demand for electricity and groundwater becomes elastic to tariff are socio-economically viable. Further, water productivity impacts of pricing would be highest when water is volumetrically allocated with rationing. Therefore, an effective power tariff policy followed by enforcement of volumetric water allocation could address the issue of efficiency, sustainability, and equity in groundwater use in India (Kumar 2005).

In a similar terms, current prices for canal irrigation water are neither likely to create sufficient revenues for maintaining the infrastructure nor to encourage efficient use of water. Charges are typically calculated per hectare and depending on the type of crop grown. As per the revised water rates for different crops grown under canal system irrigation (GoM 2011) the charges range from INR 240 per hectare per season in case of kharif food crops up to INR 1350 per hectare for cotton. Using the evapotranspiration estimated in the model simulations this results in water prices of on average 0.1 INR/ m³ for kharif and 0.06 INR/ m³ for rabi irrigation.

Ray (2007) highlights the effect of support prices on management choices. Minimum support price are an important market intervention by the Government of India to protect agricultural producers against market risks. Minimum support prices are announced by the government at the beginning of the season on the basis of recommendations of the Commission for Agricultural Costs and Prices (CACP). In case the market price for the commodity falls below the announced minimum price, government agencies purchase any production offered by the farmers at the announced minimum price. While minimum support prices are fixed for most major crops including the ones covered in our study, the mechanism could be used to increase water use efficiency (Ray 2007) by setting lower support prices for water use intensive crops.

Pricing water is a sensitive issue. Across the globe, examples have shown potential negative impacts of water prices on the poor (e.g. Dinar et al. 1997, Falk et al. 2009). Wise mechanisms need to be found to ensure that especially the poor have sufficient and reliable water supply to cover their basic needs – while still ensuring that at the large scale across all sections of the society saving of water is encouraged.

We should not be understood as generally opposing government's support to poor farmers. Farmers' management affects the provision of public goods which are enjoyed by people who are often not contributing to its generation. Our perception assessment confirms that farmers are little aware of such benefits and therefore often do not take them into account in their management decisions. Rewarding farmers for choosing practices which increase the provision of public goods. Such incentives could be understood as payments for ecosystem services rather than as subsidies. Any such policy instruments requires, however, to know which practice is affecting which ecosystem service in which context. Ecosystem service assessments – such as ours – can inform decisions on smarter support systems. They can help policy makers and development agents such as NGOs to set wise priorities regarding soil management interventions in order to achieve Land Degradation Neutrality.

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Appendices

Appendix 1a: Mixed effects models explaining simulated outcome variables for the Cotton-Fallow system (including climate variables); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha	Total ESS value in INR/ha	Net profit by evapo-transpiration in INR/m³
Year of cultivation	129.9*** (33.99)	46.35 (34.68)	0.0233*** (0.00429)
Management Parameters			
manure in kg	0.803 (0.455)	1.121* (0.438)	0.0000335 (0.0000573)
fertilizer application in kg	-68.37*** (17.96)	-89.27*** (17.27)	-0.0124*** (0.00226)
irrigation in mm	-183.7*** (8.625)	-190.5*** (8.290)	-0.0105*** (0.00109)
Climate variables			
Average minimum temperature in °C	1332.3* (548.5)	2140.8*** (527.1)	0.291*** (0.0713)
August rainfall in mm	3.183 (2.832)	7.926** (2.756)	0.000694 (0.000358)
Number of annual rainy days	-418.6*** (29.66)	-490.5*** (28.40)	-0.0597*** (0.00374)
Consecutive dry days during monsoon	55.61 (69.57)	-11.09 (67.10)	0.0191* (0.00877)
solar radiation	4816.1*** (567.1)	4878.4*** (547.6)	0.135 (0.0716)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	64431.0*** (5454.9)	64925.7*** (5205.3)	6.177*** (0.745)
Deep Vertisol	76356.3*** (3104.7)	73005.1*** (2959.3)	7.916*** (0.424)
Extremly shallow Entisols	-47093.2*** (4724.6)	-43393.4*** (4508.4)	-6.855*** (0.643)
Slightly deep Entisols	4667.3 (3702.7)	5461.8 (3532.9)	0.277 (0.503)
Shallow inceptisols	-16004.3*** (3705.8)	-14776.0*** (3539.4)	-2.360*** (0.503)
Very Deep Inceptisols	38871.9*** (4838.4)	36874.3*** (4626.6)	4.051*** (0.657)
Very Deep Vertisol	133936.3*** (2670.8)	127663*** (2548.9)	13.76*** (0.362)
Very shallow Entisols	-42134.8*** (2614.2)	-38074.7*** (2494.0)	-6.206*** (0.355)
Very shallow inceptisols	-42705.4*** (4798.9)	-39232.0*** (4586.3)	-6.160*** (0.652)
Constant	-313902.1*** (66319.0)	-187789** (66603)	-47.04*** (8.356)
Random-effects parameters			
Soil type	-1.875 (79.63)	-2.706 (7.073)	-17.31* (6.721)
Grid	8.789*** (0.0885)	8.740*** (0.0898)	-0.0950 (0.0906)
Residual	10.69*** (0.00470)	10.63*** (0.00479)	1.710*** (0.00470)
Observations	22722	21915	22722

Appendix 1b: Mixed effects models explaining simulated outcome variables for the Maize-Chickpea system (including climate variables); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha	Total ESS value in INR/ha	Net profit by evapotranspiration in INR/m^3
Year of cultivation	-144.6*** (21.01)	-66.20** (24.07)	-0.00427 (0.0023)
Management Parameters			
manure in kg	0.370 (0.291)	0.205 (0.314)	-0.000041 (0.000032)
fertilizer application in kg	21.43* (9.942)	-26.37* (10.72)	0.00257* (0.00107)
irrigation in mm	113.7*** (7.150)	120.4*** (7.709)	0.0112*** (0.000770)
Climate variables			
Average minimum temperature in °C	3451.7*** (449.1)	3531.6*** (488.5)	0.408*** (0.0484)
August rainfall in mm	26.22*** (1.749)	24.43*** (1.914)	0.00217*** (0.00019)
Number of annual rainy days	910.7*** (18.34)	1020.7*** (19.65)	0.111*** (0.00198)
Consecutive dry days during monsoon	72.92 (42.46)	163.5*** (45.98)	0.0311*** (0.00457)
solar radiation	10131.5*** (349.0)	8845.2*** (376.3)	0.536*** (0.0376)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	56319.4*** (7540.7)	59939.1*** (8095.8)	5.778*** (0.822)
Deep Vertisol	57064.8*** (4313.4)	60026.5*** (4630.0)	5.816*** (0.470)
Extremly shallow Entisols	-75009.9*** (6420.8)	-78800.3*** (6894.3)	-7.358*** (0.699)
Slightly deep Entisols	-8107.1 (4958.6)	-7515.7 (5323.2)	-0.731 (0.540)
Shallow inceptisols	-18768.5*** (4962.3)	-19373.8*** (5328.8)	-1.924*** (0.540)
Very Deep Inceptisols	-16635.0* (6481.9)	-15646.1* (6964.1)	-1.776* (0.706)
Very Deep Vertisol	112673.2*** (3571.7)	120026*** (3837.5)	11.79*** (0.389)
Very shallow Entisols	-53749.8*** (3492.4)	-55765.3*** (3749.5)	-5.402*** (0.380)
Very shallow inceptisols	-60085.0*** (6444.1)	-62700.1*** (6921.3)	-6.074*** (0.702)
Constant	18106.5 (41590.6)	-150834.3** (46545)	-11.95** (4.479)
Random-effects parameters			
Soil type	-3.871 (8.196)	-3.267 (6.311)	-13.68 (7.454)
Grid	9.189*** (0.0767)	9.260*** (0.0766)	0.0647 (0.0768)
Residual	10.19*** (0.00473)	10.24*** (0.00482)	1.051*** (0.00473)
Observations	22466	21647	22466

Appendix 1c: Mixed effects models explaining simulated outcome variables for the Sorghum-fallow system (including climate variables); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha	Total ESS value in INR/ha	Net profit by evapo-transpiration in INR/m^3
Year of cultivation	-516.5*** (9.066)	-424.1*** (9.735)	-0.0613*** (0.00177)
Management Parameters			
manure in kg	1.408*** (0.102)	1.438*** (0.103)	0.000255*** (0.00002)
fertilizer application in kg	501.1*** (8.025)	491.9*** (8.069)	0.105*** (0.00156)
irrigation in mm	0.696 (3.072)	1.352 (3.106)	0.000377 (0.000602)
Climate variables			
Average minimum temperature in °C	2368.2*** (173.1)	1449.2*** (170.6)	0.0559 (0.0324)
August rainfall in mm	-9.877*** (0.799)	-11.46*** (0.809)	-0.00179*** (0.00016)
Number of annual rainy days	-214.6*** (7.917)	-201.1*** (7.937)	-0.0341*** (0.00155)
Consecutive dry days during monsoon	-56.99** (18.17)	-59.52** (18.36)	-0.0137*** (0.00356)
solar radiation	989.2*** (152.2)	-348.2* (153.6)	-0.512*** (0.0297)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	3581.6 (2565.4)	3154.1 (2267.0)	0.859* (0.411)
Deep Vertisol	27559.9*** (1461.4)	28228.4*** (1290.8)	5.986*** (0.234)
Extremly shallow Entisols	-39870.1*** (2165.7)	-40250.4*** (1914.8)	-7.227*** (0.347)
Slightly deep Entisols	-1550.9 (1672.1)	-1616.7 (1479.2)	-0.185 (0.269)
Shallow inceptisols	-9945.6*** (1674.0)	-9609.5*** (1481.9)	-1.671*** (0.269)
Very Deep Inceptisols	-9665.0*** (2187.2)	-8170.1*** (1939.5)	-1.351*** (0.352)
Very Deep Vertisol	24770.5*** (1200.8)	26544.5*** (1069.3)	5.920*** (0.195)
Very shallow Entisols	-31122.5*** (1178.0)	-31469.2*** (1042.6)	-6.104*** (0.189)
Very shallow inceptisols	-40083.4*** (2175.7)	-39704.9*** (1926.6)	-7.431*** (0.350)
Constant	995402.6*** (17352.3)	839179.9*** (18350)	137.4*** (3.398)
Random-effects parameters			
Soil type	-3.149 (7.729)	-1.907 (6.270)	-19.07* (7.551)
Grid	8.099*** (0.0888)	7.967*** (0.0903)	-0.652*** (0.0867)
Residual	9.173*** (0.00562)	9.167*** (0.00572)	0.636*** (0.00562)
Observations	15926	15406	15926

Appendix 1d: Mixed effects models explaining simulated outcome variables for the Sorghum-Wheat system (including climate variables); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha	Total ESS value in INR/ha	Net profit by evapo-transpiration in INR/m^3
Year of cultivation	-265.1*** (14.01)	-266.7*** (16.45)	-0.0162*** (0.00141)
Management Parameters			
manure in kg	1.051*** (0.175)	0.514** (0.193)	0.000011 (0.000018)
fertilizer application in kg	319.3*** (4.705)	299.4*** (5.192)	0.0269*** (0.000475)
irrigation in mm	25.03*** (4.758)	26.53*** (5.251)	0.00202*** (0.000480)
Climate variables			
Average minimum temperature in °C	8843.5*** (316.6)	8331.5*** (354.1)	0.589*** (0.0316)
August rainfall in mm	-6.050*** (1.175)	-6.711*** (1.318)	-0.00044*** (0.00012)
Number of annual rainy days	33.59** (12.31)	82.59*** (13.50)	0.0126*** (0.00124)
Consecutive dry days during monsoon	211.4*** (28.33)	245.1*** (31.39)	0.0236*** (0.00286)
solar radiation	1197.1*** (233.2)	-154.6 (257.2)	-0.137*** (0.0235)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	23985.3* (9402.9)	24225.7* (10231.5)	2.017* (0.813)
Deep Vertisol	27806.5*** (5365.3)	27535.8*** (5837.6)	2.341*** (0.464)
Extremly shallow Entisols	-83702.1*** (7944.3)	-89355.7*** (8644.9)	-6.770*** (0.688)
Slightly deep Entisols	-5091.5 (6121.4)	-6077.5 (6660.9)	-0.508 (0.530)
Shallow inceptisols	-31823.9*** (6126.6)	-34321.6*** (6667.2)	-2.704*** (0.531)
Very Deep Inceptisols	-21465.7** (7965.3)	-22273.8* (8669.4)	-1.922** (0.690)
Very Deep Vertisol	22571.2*** (4301.0)	22027.5*** (4682.0)	1.952*** (0.373)
Very shallow Entisols	-58580.8*** (4308.1)	-61860.6*** (4688.0)	-4.965*** (0.373)
Very shallow inceptisols	-81274.1*** (7953.6)	-85961.9*** (8656.1)	-6.635*** (0.689)
Constant	323400.4*** (27868.6)	322987.3*** (31888)	22.76*** (2.805)
Random-effects parameters			
Soil type	-0.969 (6.751)	-0.913 (7.501)	-18.54** (6.785)
Grid	9.419*** (0.0774)	9.503*** (0.0776)	0.0619 (0.0785)
Residual	9.777*** (0.00475)	9.857*** (0.00484)	0.575*** (0.00496)
Observations	22227	21417	22227

Appendix 1e: Mixed effects models explaining simulated outcome variables for the Millet-Sorghum system (including climate variables); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha	Total ESS value in INR/ha	Net profit by evapo-transpiration in INR/m³
Year of cultivation	-409.8*** (13.80)	-290.1*** (14.63)	-0.0307*** (0.00168)
Management Parameters			
manure in kg	0.680** (0.216)	0.808*** (0.216)	0.000133*** (0.00003)
fertilizer application in kg	268.8*** (6.322)	251.2*** (6.348)	0.0345*** (0.000768)
irrigation in mm	56.55*** (4.689)	58.54*** (4.701)	0.00688*** (0.000570)
Climate variables			
Average minimum temperature in °C	4533.5*** (281.4)	3736.8*** (282.5)	0.529*** (0.0339)
August rainfall in mm	8.656*** (1.143)	1.526 (1.161)	0.000777*** (0.00014)
Number of annual rainy days	59.34*** (12.04)	108.4*** (12.01)	0.0162*** (0.00146)
Consecutive dry days during monsoon	86.01** (27.91)	180.0*** (28.08)	0.0265*** (0.00339)
solar radiation	762.0*** (229.4)	-1484.3*** (230.2)	-0.453*** (0.0278)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	41411.1*** (4236.7)	39423.5*** (4092.3)	4.744*** (0.493)
Deep Vertisol	54272.6*** (2401.8)	54618.5*** (2318.5)	6.484*** (0.279)
Extremly shallow Entisols	-59209.0*** (3581.9)	-56753.3*** (3461.2)	-6.872*** (0.417)
Slightly deep Entisols	-15609.6*** (2768.2)	-16316.5*** (2675.2)	-1.917*** (0.322)
Shallow inceptisols	-7581.7** (2770.7)	-7264.8** (2678.7)	-0.852** (0.322)
Very Deep Inceptisols	693.1 (3625.3)	3715.9 (3508.3)	0.0994 (0.422)
Very Deep Vertisol	60766.5*** (1976.2)	62369.5*** (1913.1)	7.739*** (0.230)
Very shallow Entisols	-44996.2*** (1950.7)	-43421.5*** (1885.4)	-5.415*** (0.227)
Very shallow inceptisols	-52945.8*** (3599.1)	-50989.6*** (3480.1)	-6.315*** (0.419)
Constant	696581.4*** (27190.0)	487358.1*** (28260)	56.37*** (3.302)
Random-effects parameters			
Soil type	-2.826 (6.976)	-2.895 (7.849)	-11.95 (7.102)
Grid	8.598*** (0.0809)	8.560*** (0.0796)	-0.465*** (0.0804)
Residual	9.746*** (0.00482)	9.732*** (0.00491)	0.730*** (0.00483)
Observations	21588	20863	21588

Appendix 1f: Mixed effects models explaining simulated outcome variables for the Mungbean-Sorghum system (including climate variables); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha	Total ESS value in INR/ha	Net profit by evapo-transpiration in INR/m³
Year of cultivation	-1078.6*** (18.79)	-1004.2*** (20.66)	-0.100*** (0.00221)
Management Parameters			
manure in kg	4.572*** (0.266)	4.797*** (0.275)	0.00063*** (0.000031)
fertilizer application in kg	286.3*** (11.68)	268.3*** (12.10)	0.0356*** (0.00138)
irrigation in mm	8.867 (6.638)	8.221 (6.870)	0.000507 (0.000782)
Climate variables			
Average minimum temperature in °C	5883.2*** (386.3)	4998.9*** (402.1)	0.547*** (0.0448)
August rainfall in mm	10.87*** (1.581)	5.101** (1.670)	0.00120*** (0.000186)
Number of annual rainy days	144.7*** (16.63)	194.8*** (17.11)	0.0299*** (0.00196)
Consecutive dry days during monsoon	179.5*** (37.99)	276.9*** (39.43)	0.0455*** (0.00448)
solar radiation	8550.4*** (309.4)	6783.4*** (320.4)	0.219*** (0.0364)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	35256.7*** (5892.7)	32143.2*** (5963.2)	3.609*** (0.638)
Deep Vertisol	52715.8*** (3358.9)	52341.3*** (3396.3)	6.173*** (0.364)
Extremly shallow Entisols	-82346.2*** (5033.0)	-81198.3*** (5094.1)	-9.131*** (0.546)
Slightly deep Entisols	-16570.0*** (3854.9)	-17852.7*** (3901.4)	-2.202*** (0.418)
Shallow inceptisols	-13756.1*** (3859.9)	-13405.2*** (3905.9)	-1.408*** (0.419)
Very Deep Inceptisols	-5673.1 (5034.0)	-3542.9 (5096.0)	-0.704 (0.546)
Very Deep Vertisol	57037.7*** (2754.6)	58182.3*** (2790.9)	7.485*** (0.300)
Very shallow Entisols	-60583.7*** (2725.4)	-59571.1*** (2757.8)	-6.934*** (0.296)
Very shallow inceptisols	-69860.7*** (5059.0)	-68783.7*** (5124.0)	-7.907*** (0.550)
Constant	1903159.0*** (37037)	1779678*** (39846)	187.8*** (4.364)
Random-effects parameters			
Soil type	-2.797 (8.199)	-2.454 (6.235)	-11.49 (7.037)
Grid	8.938*** (0.0794)	8.948*** (0.0783)	-0.196* (0.0790)
Residual	10.15*** (0.00443)	10.16*** (0.00451)	1.099*** (0.00443)
Observations	25622	24670	25622

Appendix 1g: Mixed effects models explaining simulated outcome variables for the Pigeonpea-Fallow system (including climate variables); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha	Total ESS value in INR/ha	Net profit by evapo-transpiration in INR/m^3
Year of cultivation	-26.85 (13.74)	87.90*** (15.71)	0.0601*** (0.00275)
Management Parameters			
manure in kg	0.169 (0.221)	0.173 (0.236)	0.000063 (0.000045)
fertilizer application in kg	-18.51* (8.644)	-67.62*** (9.235)	-0.00145 (0.00173)
irrigation in mm	46.09*** (4.721)	55.42*** (5.044)	0.0104*** (0.000944)
Climate variables			
Average minimum temperature in ^{o}C	1602.7*** (270.4)	1013.3*** (290.9)	-0.179*** (0.0535)
August rainfall in mm	17.38*** (1.154)	17.66*** (1.250)	0.00418*** (0.000231)
Number of annual rainy days	320.3*** (12.01)	377.6*** (12.78)	0.0941*** (0.00240)
Consecutive dry days during monsoon	-413.4*** (27.98)	-412.5*** (30.01)	-0.0938*** (0.00560)
solar radiation	8704.4*** (235.1)	8479.6*** (251.4)	0.726*** (0.0470)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	5414.5 (5285.0)	5974.8 (5537.9)	0.865 (0.973)
Deep Vertisol	10530.6*** (3009.9)	10069.9** (3154.1)	2.596*** (0.554)
Extremly shallow Entisols	-61174.5*** (4462.7)	-62503.9*** (4677.4)	-13.05*** (0.822)
Slightly deep Entisols	-7432.1* (3445.3)	-6478.2 (3610.5)	-1.498* (0.634)
Shallow inceptisols	-10192.5** (3446.6)	-9236.0* (3612.9)	-1.786** (0.635)
Very Deep Inceptisols	-4727.0 (4481.0)	-2476.6 (4699.0)	-0.314 (0.825)
Very Deep Vertisol	7828.9** (2433.2)	8578.5*** (2551.8)	2.497*** (0.449)
Very shallow Entisols	-38275.9*** (2422.4)	-38138.7*** (2538.7)	-8.619*** (0.446)
Very shallow inceptisols	-48092.3*** (4476.9)	-47932.6*** (4693.8)	-10.50*** (0.825)
Constant	-79245.7** (26335.4)	-301865*** (29550)	-115.3*** (5.264)
Random-effects parameters			
Soil type	-5.354 (6.190)	-5.167 (54.58)	-13.34 (7.259)
Grid	8.831*** (0.0785)	8.877*** (0.0780)	0.228** (0.0791)
Residual	9.735*** (0.00491)	9.784*** (0.00499)	1.218*** (0.00491)
Observations	20876	20149	20876

Appendix 1h: Mixed effects models explaining simulated outcome variables for the Rice-Chickpea system (including climate variables); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	Net profit in INR/ha	Total ESS value in INR/ha	Net profit by evapo-transpiration in INR/m³
Year of cultivation	-304.9*** (16.38)	-472.5*** (17.82)	-0.0263*** (0.00183)
Management Parameters			
manure in kg	1.398*** (0.260)	1.807*** (0.284)	-0.00008** (0.000030)
fertilizer application in kg	156.9*** (7.402)	115.8*** (8.059)	0.0139*** (0.000826)
irrigation in mm	-10.74*** (1.266)	141.9*** (3.075)	-0.000163 (0.000142)
Climate variables			
Average minimum temperature in °C	2269.7*** (314.2)	5409.5*** (369.9)	0.331*** (0.0359)
August rainfall in mm	-16.02*** (1.289)	-6.321*** (1.433)	-0.00242*** (0.00015)
Number of annual rainy days	107.3*** (15.03)	846.5*** (19.84)	0.0343*** (0.00168)
Consecutive dry days during monsoon	390.7*** (31.09)	303.3*** (34.25)	0.0666*** (0.00347)
solar radiation	1542.6*** (257.5)	707.2* (278.8)	-0.338*** (0.0288)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	49134.3*** (4390.1)	105773*** (8140.4)	3.569*** (0.547)
Deep Vertisol	74099.1*** (2509.7)	102125.2*** (4627)	6.864*** (0.313)
Extremly shallow Entisols	-56090.6*** (3743.8)	-57524.0*** (6834.2)	-4.869*** (0.466)
Slightly deep Entisols	-15098.2*** (2931.9)	26662.6*** (5389.8)	-1.885*** (0.364)
Shallow inceptisols	-6157.4* (2895.1)	-8123.8 (5270.9)	-0.774* (0.360)
Very Deep Inceptisols	-1844.1 (3798.9)	11565.3 (6880.0)	-0.489 (0.471)
Very Deep Vertisol	119715.7*** (2135.1)	172703.5*** (3859)	10.97*** (0.263)
Very shallow Entisols	-32939.0*** (2060.1)	-16264.3*** (3760.2)	-3.235*** (0.256)
Very shallow inceptisols	-43882.2*** (3771.7)	-37056.5*** (6867.6)	-4.144*** (0.469)
Constant	562555.2*** (32348.8)	609902.3*** (34786)	52.62*** (3.611)
Random-effects parameters			
Soil type	-2.382 (7.879)	-2.981 (6.386)	-12.84 (8.265)
Grid	8.634*** (0.0811)	9.261*** (0.0786)	-0.350*** (0.0827)
Residual	9.878*** (0.00471)	9.945*** (0.00480)	0.778*** (0.00471)
Observations	22623	21795	22623

Appendix 1i: Mixed effects models explaining simulated outcome variables for the Soybean-Chickpea system (including climate variables); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	Net profit in INR/ha	Total ESS value in INR/ha	Net profit by evapo-transpiration in INR/m^3
Year of cultivation	-252.6*** (19.71)	-225.6*** (23.64)	-0.0154*** (0.00219)
Management Parameters			
manure in kg	2.001*** (0.272)	3.755*** (0.304)	0.000071* (0.000031)
fertilizer application in kg	-37.11* (14.82)	37.89* (16.97)	-0.00445** (0.00165)
irrigation in mm	106.5*** (6.688)	55.80*** (7.672)	0.0106*** (0.000743)
Climate variables			
Average minimum temperature in °C	1649.5*** (413.9)	985.3* (474.7)	0.120* (0.0467)
August rainfall in mm	38.02*** (1.623)	37.98*** (1.858)	0.00401*** (0.000181)
Number of annual rainy days	695.3*** (17.21)	788.7*** (19.34)	0.0911*** (0.00191)
Consecutive dry days during monsoon	65.03 (40.05)	169.6*** (45.53)	0.0388*** (0.00445)
solar radiation	8559.9*** (329.6)	8455.0*** (373.1)	0.470*** (0.0367)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	59639.6*** (6875.8)	63322.3*** (7765.5)	6.585*** (0.844)
Deep Vertisol	58954.9*** (3920.5)	62515.6*** (4425.1)	6.542*** (0.481)
Extremly shallow Entisols	-54303.6*** (5827.3)	-55264.7*** (6578.0)	-5.512*** (0.714)
Slightly deep Entisols	-6521.5 (4501.1)	-6300.5 (5079.3)	-0.686 (0.552)
Shallow inceptisols	-13575.3** (4504.6)	-11907.2* (5085.2)	-1.462** (0.552)
Very Deep Inceptisols	-5110.5 (5886.1)	-2885.0 (6648.3)	-0.668 (0.720)
Very Deep Vertisol	120574.9*** (3244.5)	124724.7*** (3666)	13.56*** (0.396)
Very shallow Entisols	-37076.7*** (3170.7)	-37149.6*** (3578.5)	-3.971*** (0.388)
Very shallow inceptisols	-40593.4*** (5850.6)	-39387.8*** (6606.2)	-4.268*** (0.717)
Constant	291508.6*** (39061.5)	217556.7*** (45789)	16.93*** (4.344)
Random-effects parameters			
Soil type	-3.729 (6.490)	-3.615 (6.205)	-14.45 (181.2)
Grid	9.092*** (0.0759)	9.212*** (0.0762)	0.0892 (0.0754)
Residual	10.10*** (0.00483)	10.16*** (0.00513)	0.998*** (0.00483)
Observations	21555	19091	21555

Appendix 1j: Mixed effects models explaining simulated outcome variables for the Sorghum-Chickpea system (including climate variables); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	Net profit in INR/ha	Total ESS value in INR/ha	Net profit by evapo-transpiration in INR/m^3
Year of cultivation	-78.45*** (17.31)	106.4*** (19.70)	0.0108*** (0.00177)
Management Parameters			
manure in kg	4.510*** (0.191)	4.352*** (0.205)	0.000326*** (0.00002)
fertilizer application in kg	416.4*** (12.47)	394.2*** (13.33)	0.0417*** (0.00128)
irrigation in mm	65.85*** (5.907)	71.39*** (6.328)	0.00580*** (0.000605)
Climate variables			
Average minimum temperature in °C	5820.7*** (369.5)	4220.1*** (394.2)	0.432*** (0.0380)
August rainfall in mm	16.44*** (1.448)	8.131*** (1.574)	0.00124*** (0.000148)
Number of annual rainy days	388.8*** (15.17)	510.8*** (16.14)	0.0552*** (0.00155)
Consecutive dry days during monsoon	129.1*** (35.03)	284.2*** (37.68)	0.0291*** (0.00359)
solar radiation	799.7** (287.9)	-1667.1*** (308.0)	-0.516*** (0.0295)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	63702.1*** (6519.2)	67502.3*** (6336.3)	6.712*** (0.681)
Deep Vertisol	79730.3*** (3727.8)	84908.3*** (3623.8)	7.878*** (0.389)
Extremly shallow Entisols	-69403.3*** (5546.3)	-69945.5*** (5400.7)	-6.331*** (0.579)
Slightly deep Entisols	-1461.9 (4283.3)	-760.3 (4172.3)	-0.0812 (0.447)
Shallow inceptisols	-19224.4*** (4285.5)	-19030.4*** (4176.0)	-1.855*** (0.447)
Very Deep Inceptisols	-10988.3* (5589.9)	-7428.3 (5453.8)	-1.045 (0.583)
Very Deep Vertisol	129724.6*** (3076.9)	140436.6*** (3014)	12.90*** (0.321)
Very shallow Entisols	-51381.1*** (3016.4)	-53151.8*** (2939.2)	-5.024*** (0.315)
Very shallow inceptisols	-64619.1*** (5565.8)	-64242.8*** (5425.1)	-6.074*** (0.581)
Constant	4964.9 (34255.5)	-319945*** (38094)	-22.85*** (3.510)
Random-effects parameters			
Soil type	-5.202 (7.773)	-3.646 (8.363)	-14.78 (264.3)
Grid	9.045*** (0.0790)	9.013*** (0.0780)	-0.122 (0.0779)
Residual	10.000*** (0.00470)	10.05*** (0.00479)	0.814*** (0.00470)
Observations	22714	21881	22714

Appendix 1k: Mixed effects models explaining simulated outcome variables for the Soybean-Maize system (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha	Total ESS value in INR/ha	Net profit by evapo-transpiration in INR/m^3
Year of cultivation	-442.5*** (16.54)	-480.5*** (19.38)	-0.0352*** (0.00169)
Management Parameters			
manure in kg	0.956*** (0.219)	0.937*** (0.242)	0.00010*** (0.000023)
fertilizer application in kg	37.12*** (6.432)	-14.72* (7.102)	0.00415*** (0.000657)
irrigation in mm	54.99*** (5.629)	66.21*** (6.218)	0.00555*** (0.000575)
Climate variables			
Average minimum temperature in °C	3807.3*** (347.0)	3748.0*** (391.6)	0.332*** (0.0354)
August rainfall in mm	24.09*** (1.356)	25.87*** (1.519)	0.00271*** (0.000139)
Number of annual rainy days	311.5*** (14.44)	365.3*** (15.87)	0.0397*** (0.00148)
Consecutive dry days during monsoon	8.724 (33.57)	19.51 (37.26)	0.0138*** (0.00343)
solar radiation	7430.2*** (277.0)	7662.8*** (306.3)	0.357*** (0.0283)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	17245.4** (5266.7)	17259.6** (6203.7)	1.658** (0.534)
Deep Vertisol	44684.7*** (2988.1)	45310.7*** (3522.0)	4.610*** (0.303)
Extremly shallow Entisols	-60336.4*** (4443.5)	-67056.8*** (5234.7)	-5.892*** (0.451)
Slightly deep Entisols	-14748.5*** (3433.1)	-17651.6*** (4041.9)	-1.597*** (0.348)
Shallow inceptisols	-12867.3*** (3436.7)	-12945.6** (4047.1)	-1.287*** (0.349)
Very Deep Inceptisols	-9582.6* (4497.2)	-9509.9 (5294.4)	-1.165* (0.456)
Very Deep Vertisol	89049.9*** (2452.2)	91259.6*** (2882.7)	9.538*** (0.249)
Very shallow Entisols	-43115.7*** (2419.2)	-46762.9*** (2847.7)	-4.428*** (0.246)
Very shallow inceptisols	-50330.9*** (4465.8)	-55035.9*** (5259.7)	-5.111*** (0.453)
Constant	660196.8*** (32817.1)	706288.3*** (37571)	55.87*** (3.353)
Random-effects parameters			
Soil type	-2.931 (8.323)	-3.442 (7.112)	-12.44 (7.982)
Grid	8.815*** (0.0775)	8.982*** (0.0772)	-0.381*** (0.0771)
Residual	9.921*** (0.00486)	10.00*** (0.00495)	0.732*** (0.00486)
Observations	21259	20486	21259

Appendix 2a: Mixed effects models explaining simulated outcome variables for the Cotton-Fallow system (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo-transpiration in INR/m^3
Year of cultivation	212.4*** (32.68)	187.6*** (32.52)	0.0298*** (0.00412)
Management parameters			
manure in kg	0.381 (0.463)	0.615 (0.445)	-0.0000491 (0.0000583)
fertilizer in kg	-57.78** (17.89)	-77.42*** (17.19)	-0.0107*** (0.00226)
irrigation in mm	-190.4*** (8.644)	-198.3*** (8.301)	-0.0117*** (0.00109)
Climate scenarios (reference are observed climate data over the past 30 years)			
Cool wet	-9749.7*** (738.5)	-9614.1*** (709.5)	-1.040*** (0.0931)
Hot dry	13904.5*** (728.0)	14592.5*** (699.5)	1.866*** (0.0917)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	60920.6*** (4973.3)	60859.3*** (4657.7)	5.653*** (0.649)
Deep Vertisol	77262.7*** (2846.8)	74254.0*** (2663.1)	8.079*** (0.372)
Extremly shallow Entisols	-46637.9*** (4302.5)	-42150.2*** (4031.6)	-6.883*** (0.561)
Slightly deep Entisols	5215.8 (3423.7)	6540.6* (3212.8)	0.370 (0.445)
Shallow inceptisols	-18056.3*** (3396.7)	-16362.7*** (3190.5)	-2.539*** (0.442)
Very Deep Inceptisols	35430.7*** (4353.7)	34487.2*** (4090.9)	3.805*** (0.567)
Very Deep Vertisol	131989.5*** (2299.3)	126905.7*** (2152.7)	13.72*** (0.300)
Very shallow Entisols	-44450.2*** (2385.7)	-40035.9*** (2236.7)	-6.448*** (0.311)
Very shallow inceptisols	-43440.5*** (4371.3)	-39015.7*** (4108.4)	-6.123*** (0.569)
Constant	-375417.9*** (65279.9)	-350844.0*** (64962.0)	-53.50*** (8.228)
Random-effects parameters			
Soil type	-2.034 (84.55)	-1.462 (54.22)	-11.90 (6.969)
Grid	8.690*** (0.0873)	8.617*** (0.0880)	-0.246** (0.0918)
Residual	10.68*** (0.00470)	10.62*** (0.00479)	1.697*** (0.00470)
Observations	22722	21915	22722

Appendix 2b: Mixed effects models explaining simulated outcome variables for the Maize-Chickpea system (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo-transpiration in INR/m^3
Year of cultivation	-117.8*** (22.30)	-16.41 (24.96)	-0.00714** (0.00240)
Management parameters			
manure in kg	-0.243 (0.328)	-0.230 (0.354)	-0.0000320 (0.0000353)
fertilizer in kg	23.84* (10.77)	-24.58* (11.62)	0.00253* (0.00116)
irrigation in mm	112.8*** (7.743)	119.5*** (8.355)	0.0111*** (0.000833)
Climate scenarios (reference are observed climate data over the past 30 years)			
Cool wet	4166.4*** (479.9)	3617.7*** (517.8)	0.214*** (0.0517)
Hot dry	1227.0* (480.7)	143.5 (518.6)	-0.329*** (0.0517)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	46592.8*** (10271.9)	49453.1*** (10993.7)	4.709*** (1.075)
Deep Vertisol	58318.9*** (5879.1)	61216.9*** (6291.9)	5.926*** (0.615)
Extremly shallow Entisols	-55391.8*** (8705.7)	-58757.8*** (9317.7)	-5.424*** (0.911)
Slightly deep Entisols	-9558.5 (6736.2)	-9520.3 (7210.2)	-0.894 (0.705)
Shallow inceptisols	-7793.1 (6727.2)	-7984.9 (7201.8)	-0.643 (0.704)
Very Deep Inceptisols	5098.5 (8730.3)	7165.7 (9347.8)	0.708 (0.914)
Very Deep Vertisol	129578.8*** (4718.4)	137830.4*** (5050.6)	13.75*** (0.494)
Very shallow Entisols	-42846.3*** (4730.5)	-44178.6*** (5063.0)	-4.177*** (0.495)
Very shallow inceptisols	-44845.3*** (8719.3)	-47093.5*** (9334.9)	-4.410*** (0.913)
Constant	277649.1*** (44678.4)	46106.8 (49989.2)	18.64*** (4.808)
Random-effects parameters			
Soil type	-0.0378 (30.33)	0.160 (31.09)	-16.03* (7.374)
Grid	9.505*** (0.0752)	9.573*** (0.0752)	0.340*** (0.0752)
Residual	10.27*** (0.00473)	10.32*** (0.00482)	1.130*** (0.00473)
Observations	22466	21647	22466

Appendix 2c: Mixed effects models explaining simulated outcome variables for the Sorghum-fallow system (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo-transpiration in INR/m³
Year of cultivation	-478.1*** (9.038)	-415.4*** (9.366)	-0.0686*** (0.00175)
Management parameters			
manure in kg	1.350*** (0.112)	1.469*** (0.112)	0.000298*** (0.0000216)
fertilizer in kg	501.6*** (8.364)	493.1*** (8.373)	0.106*** (0.00162)
irrigation in mm	0.456 (3.209)	1.199 (3.221)	0.000384 (0.000620)
Climate scenarios (reference are observed climate data over the past 30 years)			
Cool wet	-1140.1*** (201.4)	-1306.6*** (202.2)	-0.340*** (0.0389)
Hot dry	1580.1*** (201.0)	875.5*** (201.7)	-0.100** (0.0388)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	1521.9 (2432.2)	2360.2 (2358.1)	0.969 (0.513)
Deep Vertisol	28033.1*** (1388.9)	28286.8*** (1346.7)	5.926*** (0.293)
Extremly shallow Entisols	-39245.4*** (2049.1)	-41466.2*** (1986.4)	-7.835*** (0.432)
Slightly deep Entisols	-1212.9 (1591.9)	-1155.2 (1544.1)	-0.105 (0.335)
Shallow inceptisols	-10495.4*** (1588.0)	-10717.3*** (1540.7)	-1.983*** (0.335)
Very Deep Inceptisols	-9820.2*** (2058.8)	-9921.5*** (1997.7)	-1.902*** (0.434)
Very Deep Vertisol	25486.3*** (1108.7)	25847.5*** (1075.0)	5.557*** (0.234)
Very shallow Entisols	-32417.3*** (1116.4)	-33247.8*** (1082.6)	-6.467*** (0.235)
Very shallow inceptisols	-39294.8*** (2057.2)	-40338.7*** (1996.1)	-7.784*** (0.434)
Constant	979762.0*** (18059.0)	836861.9*** (18715.4)	141.5*** (3.489)
Random-effects parameters			
Soil type	-2.226 (6.330)	-2.317 (7.929)	-11.80 (174.3)
Grid	8.044*** (0.0793)	8.011*** (0.0797)	-0.415*** (0.0781)
Residual	9.217*** (0.00562)	9.204*** (0.00571)	0.665*** (0.00562)
Observations	15926	15406	15926

Appendix 2d: Mixed effects models explaining simulated outcome variables for the Sorghum-Wheat system (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo-transpiration in INR/m³
Year of cultivation	-181.5*** (13.95)	-182.2*** (15.58)	-0.0137*** (0.00134)
Management parameters			
manure in kg	2.144*** (0.184)	2.327*** (0.198)	0.000226*** (0.0000176)
fertilizer in kg	322.6*** (4.785)	304.8*** (5.153)	0.0275*** (0.000459)
irrigation in mm	25.80*** (4.837)	27.97*** (5.211)	0.00218*** (0.000464)
Climate scenarios (reference are observed climate data over the past 30 years)			
Cool wet	-5452.5*** (301.2)	-8283.1*** (324.4)	-0.956*** (0.0289)
Hot dry	-5558.7*** (300.4)	-10349.3*** (323.6)	-1.286*** (0.0288)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	13280.6* (6003.6)	14125.7* (6717.2)	1.288* (0.557)
Deep Vertisol	30654.1*** (3428.1)	30104.0*** (3835.2)	2.523*** (0.318)
Extremly shallow Entisols	-72495.2*** (5079.6)	-79062.4*** (5681.7)	-6.034*** (0.471)
Slightly deep Entisols	-4932.0 (3927.3)	-6006.7 (4391.9)	-0.518 (0.364)
Shallow inceptisols	-25378.7*** (3926.9)	-27903.3*** (4392.1)	-2.194*** (0.364)
Very Deep Inceptisols	-6605.4 (5091.3)	-7923.9 (5695.2)	-0.798 (0.472)
Very Deep Vertisol	36662.4*** (2728.4)	35753.0*** (3052.0)	3.004*** (0.253)
Very shallow Entisols	-54680.3*** (2760.4)	-57936.7*** (3086.8)	-4.629*** (0.256)
Very shallow inceptisols	-69319.2*** (5088.9)	-74659.2*** (5692.9)	-5.780*** (0.472)
Constant	382375.5*** (27936.3)	345536.6*** (31208.2)	29.12*** (2.678)
Random-effects parameters			
Soil type	-6.458 (80.69)	-6.844 (7.273)	-15.65* (6.401)
Grid	8.965*** (0.0767)	9.078*** (0.0766)	-0.322*** (0.0771)
Residual	9.793*** (0.00475)	9.849*** (0.00484)	0.541*** (0.00475)
Observations	22227	21417	22227

Appendix 2e: Mixed effects models explaining simulated outcome variables for the Millet-Sorghum system (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapotranspiration in INR/m^3
Year of cultivation	-377.1*** (13.54)	-281.2*** (13.98)	-0.0331*** (0.00164)
Management parameters			
manure in kg	0.264 (0.219)	0.276 (0.219)	0.0000243 (0.0000265)
fertilizer in kg	260.5*** (6.374)	241.1*** (6.370)	0.0325*** (0.000771)
irrigation in mm	56.40*** (4.701)	58.02*** (4.692)	0.00684*** (0.000568)
Climate scenarios (reference are observed climate data over the past 30 years)			
Cool wet	1045.9*** (292.0)	1875.3*** (291.9)	0.533*** (0.0353)
Hot dry	4801.3*** (291.5)	5568.4*** (290.6)	0.971*** (0.0352)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	35205.3*** (4536.8)	34313.9*** (4578.3)	4.024*** (0.563)
Deep Vertisol	55783.0*** (2579.5)	55532.3*** (2603.2)	6.600*** (0.320)
Extremly shallow Entisols	-51799.6*** (3826.7)	-51738.4*** (3861.7)	-6.215*** (0.475)
Slightly deep Entisols	-15531.7*** (2970.1)	-16374.0*** (2997.0)	-1.909*** (0.368)
Shallow inceptisols	-3215.2 (2963.3)	-3501.1 (2991.2)	-0.274 (0.368)
Very Deep Inceptisols	10702.1** (3845.8)	11848.0** (3882.8)	1.370** (0.477)
Very Deep Vertisol	69708.5*** (2055.0)	69701.6*** (2073.7)	8.867*** (0.255)
Very shallow Entisols	-41548.3*** (2084.1)	-40688.2*** (2102.7)	-4.967*** (0.259)
Very shallow inceptisols	-45146.2*** (3837.4)	-44992.7*** (3873.9)	-5.409*** (0.476)
Constant	752870.2*** (27081.1)	533279.9*** (27963.2)	65.65*** (3.275)
Random-effects parameters			
Soil type	-3.391 (6.049)	-3.530 (6.666)	-13.30 (95.31)
Grid	8.672*** (0.0777)	8.682*** (0.0776)	-0.321*** (0.0773)
Residual	9.749*** (0.00482)	9.730*** (0.00491)	0.728*** (0.00482)
Observations	21588	20863	21588

Appendix 2f: Mixed effects models explaining simulated outcome variables for the Mungbean-Sorghum system (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo-transpiration in INR/m^3
Year of cultivation	-948.0*** (16.57)	-851.9*** (17.52)	-0.0955*** (0.00192)
Management parameters			
manure in kg	1.737*** (0.251)	1.770*** (0.256)	0.000240*** (0.0000290)
fertilizer in kg	264.3*** (10.55)	244.5*** (10.76)	0.0325*** (0.00122)
irrigation in mm	60.73*** (6.127)	63.71*** (6.250)	0.00761*** (0.000710)
Climate scenarios (reference are observed climate data over the past 30 years)			
Cool wet	-1892.4*** (376.5)	-1186.2** (384.0)	0.123** (0.0436)
Hot dry	26261.8*** (366.1)	27266.4*** (373.5)	3.231*** (0.0424)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	28707.3*** (7014.3)	26820.2*** (7105.4)	3.084*** (0.757)
Deep Vertisol	57982.7*** (4006.7)	57303.7*** (4057.3)	6.758*** (0.432)
Extremly shallow Entisols	-66453.9*** (5951.6)	-67339.9*** (6027.6)	-7.674*** (0.643)
Slightly deep Entisols	-18778.1*** (4583.6)	-20069.0*** (4643.3)	-2.427*** (0.495)
Shallow inceptisols	-10688.1* (4578.5)	-11074.3* (4637.4)	-1.016* (0.494)
Very Deep Inceptisols	6967.9 (5930.1)	6928.7 (6005.9)	0.698 (0.640)
Very Deep Vertisol	71086.7*** (3184.3)	70709.3*** (3224.6)	9.102*** (0.344)
Very shallow Entisols	-53521.0*** (3224.9)	-53014.8*** (3265.8)	-6.041*** (0.348)
Very shallow inceptisols	-56807.0*** (5964.7)	-57589.5*** (6043.3)	-6.507*** (0.644)
Constant	1934390*** (33179.2)	1715772*** (35077.7)	195.0*** (3.843)
Random-effects parameters			
Soil type	-1.211 (35.46)	-1.239 (45.53)	-10.99 (6.621)
Grid	9.122*** (0.0755)	9.134*** (0.0756)	-0.0139 (0.0759)
Residual	10.04*** (0.00443)	10.04*** (0.00451)	0.978*** (0.00443)
Observations	25622	24670	25622

Appendix 2g: Mixed effects models explaining simulated outcome variables for the Pigeonpea-Fallow system (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo-transpiration in INR/m³
Year of cultivation	110.4*** (13.92)	268.9*** (15.30)	0.0684*** (0.00279)
Management parameters			
manure in kg	-0.747** (0.237)	-0.846*** (0.252)	-0.000144** (0.0000475)
fertilizer in kg	5.515 (9.213)	-41.14*** (9.784)	0.00386* (0.00184)
irrigation in mm	43.65*** (5.009)	52.53*** (5.320)	0.00973*** (0.00100)
Climate scenarios (reference are observed climate data over the past 30 years)			
Cool wet	5704.5*** (325.7)	6101.2*** (346.0)	1.233*** (0.0652)
Hot dry	7928.3*** (309.9)	8967.0*** (329.0)	1.807*** (0.0621)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	1922.5 (6366.2)	3183.9 (6969.0)	0.748 (1.375)
Deep Vertisol	11158.7** (3631.7)	10402.2** (3976.2)	2.484** (0.785)
Extremly shallow Entisols	-50696.6*** (5370.1)	-52373.4*** (5878.6)	-11.67*** (1.160)
Slightly deep Entisols	-7903.3 (4152.7)	-7100.8 (4544.7)	-1.591 (0.897)
Shallow inceptisols	-5881.6 (4148.1)	-5138.3 (4540.8)	-0.986 (0.896)
Very Deep Inceptisols	4596.4 (5371.7)	6234.3 (5881.9)	1.212 (1.161)
Very Deep Vertisol	14957.1*** (2884.4)	15170.7*** (3157.5)	3.580*** (0.623)
Very shallow Entisols	-33477.3*** (2914.6)	-33243.0*** (3190.1)	-7.576*** (0.630)
Very shallow inceptisols	-40950.6*** (5379.7)	-41494.6*** (5889.9)	-9.465*** (1.162)
Constant	-143478.5*** (27876.2)	-468861.3*** (30644.1)	-119.3*** (5.585)
Random-effects parameters			
Soil type	-6.731 (6.280)	-0.273 (50.70)	-16.77* (6.963)
Grid	9.022*** (0.0760)	9.113*** (0.0759)	0.584*** (0.0759)
Residual	9.794*** (0.00491)	9.837*** (0.00499)	1.278*** (0.00490)
Observations	20876	20149	20876

Appendix 2h: Mixed effects models explaining simulated outcome variables for the Rice-Chickpea system (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapotranspiration in INR/m^3
Year of cultivation	-285.8*** (12.55)	-457.3*** (15.57)	-0.0351*** (0.00165)
Management parameters			
manure in kg	0.296 (0.217)	0.281 (0.267)	0.0000146 (0.0000286)
fertilizer in kg	163.1*** (5.982)	123.9*** (7.369)	0.0139*** (0.000787)
irrigation in mm	-17.07*** (0.881)	33.44*** (1.966)	-0.00229*** (0.000116)
Climate scenarios (reference are observed climate data over the past 30 years)			
Cool wet	-10587.0*** (264.3)	-11255.1*** (336.6)	-1.459*** (0.0348)
Hot dry	19199.5*** (259.9)	16085.0*** (322.2)	0.556*** (0.0342)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	42524.0*** (3843.1)	55412.9*** (5790.7)	2.226*** (0.448)
Deep Vertisol	73833.6*** (2199.0)	86307.5*** (3302.6)	6.585*** (0.257)
Extremly shallow Entisols	-54423.5*** (3263.1)	-58077.4*** (4884.8)	-4.897*** (0.381)
Slightly deep Entisols	-17855.1*** (2555.8)	-14259.8*** (3847.7)	-2.736*** (0.300)
Shallow inceptisols	-4910.4 (2528.6)	-3020.9 (3776.4)	-0.486 (0.296)
Very Deep Inceptisols	-798.8 (3284.1)	9649.6* (4915.6)	-0.275 (0.385)
Very Deep Vertisol	119636.5*** (1784.3)	147032.7*** (2727.5)	10.70*** (0.209)
Very shallow Entisols	-34343.2*** (1790.9)	-34439.7*** (2696.7)	-3.598*** (0.210)
Very shallow inceptisols	-43598.5*** (3277.3)	-48327.2*** (4910.2)	-4.254*** (0.384)
Constant	619116.2*** (25345.5)	874223.1*** (31121.1)	75.80*** (3.333)
Random-effects parameters			
Soil type	-2.979 (7.628)	-4.695 (6.660)	-11.68 (6.300)
Grid	8.509*** (0.0769)	8.920*** (0.0766)	-0.553*** (0.0775)
Residual	9.665*** (0.00471)	9.855*** (0.00480)	0.729*** (0.00471)
Observations	22623	21795	22623

Appendix 2i: Mixed effects models explaining simulated outcome variables for the Soybean-Chickpea system (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo-transpiration in INR/m³
Year of cultivation	-251.2*** (19.55)	-195.6*** (23.31)	-0.0212*** (0.00226)
Management parameters			
manure in kg	-0.510 (0.286)	-0.448 (0.336)	-0.0000595 (0.0000331)
fertilizer in kg	-23.60 (14.99)	-84.23*** (17.69)	-0.00381* (0.00174)
irrigation in mm	101.8*** (6.762)	113.2*** (8.008)	0.0103*** (0.000783)
Climate scenarios (reference are observed climate data over the past 30 years)			
Cool wet	2829.0*** (423.5)	1705.4*** (467.3)	-0.0779 (0.0490)
Hot dry	20299.6*** (422.4)	20112.0*** (526.2)	1.282*** (0.0489)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	49998.1*** (9605.6)	54416.7*** (10846.4)	5.715*** (1.123)
Deep Vertisol	60006.2*** (5485.9)	63692.3*** (6192.7)	6.659*** (0.641)
Extremly shallow Entisols	-38187.7*** (8113.5)	-39757.4*** (9158.5)	-3.955*** (0.949)
Slightly deep Entisols	-7633.2 (6274.3)	-8039.6 (7083.1)	-0.824 (0.734)
Shallow inceptisols	-4716.6 (6267.3)	-3688.7 (7076.2)	-0.418 (0.733)
Very Deep Inceptisols	12594.4 (8133.6)	14209.5 (9184.9)	1.318 (0.951)
Very Deep Vertisol	133742.6*** (4392.6)	142059.0*** (4961.1)	15.05*** (0.514)
Very shallow Entisols	-27479.8*** (4407.1)	-27654.2*** (4975.0)	-2.868*** (0.515)
Very shallow inceptisols	-28105.5*** (8124.6)	-27879.3** (9173.5)	-2.946** (0.950)
Constant	522198.1*** (39179.9)	388541.7*** (46700.2)	45.06*** (4.537)
Random-effects parameters			
Soil type	-1.261 (6.884)	-0.661 (7.359)	-18.14* (7.060)
Grid	9.436*** (0.0750)	9.557*** (0.0751)	0.383*** (0.0749)
Residual	10.11*** (0.00483)	10.19*** (0.00513)	1.050*** (0.00483)
Observations	21555	19091	21555

Appendix 2j: Mixed effects models explaining simulated outcome variables for the Sorghum-Chickpea system (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo-transpiration in INR/m^3
Year of cultivation	-71.39*** (16.94)	67.69*** (19.05)	0.00326 (0.00181)
Management parameters			
manure in kg	2.785*** (0.201)	2.989*** (0.218)	0.000299*** (0.0000216)
fertilizer in kg	416.8*** (12.45)	394.3*** (13.47)	0.0416*** (0.00133)
irrigation in mm	64.47*** (5.899)	70.28*** (6.396)	0.00581*** (0.000632)
Climate scenarios (reference are observed climate data over the past 30 years)			
Cool wet	3894.0*** (367.5)	2185.6*** (398.5)	-0.0857* (0.0394)
Hot dry	12963.0*** (367.6)	11176.2*** (398.5)	0.342*** (0.0394)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	54480.8*** (6325.9)	60027.8*** (6619.4)	5.983*** (0.663)
Deep Vertisol	81619.1*** (3624.5)	85999.0*** (3793.2)	7.970*** (0.380)
Extremly shallow Entisols	-56709.4*** (5375.8)	-60142.2*** (5627.8)	-5.429*** (0.563)
Slightly deep Entisols	-1715.7 (4168.9)	-1537.8 (4366.3)	-0.120 (0.437)
Shallow inceptisols	-10937.4** (4160.2)	-11543.1** (4358.0)	-1.019* (0.436)
Very Deep Inceptisols	7068.5 (5393.5)	8170.1 (5649.8)	0.677 (0.565)
Very Deep Vertisol	144897.0*** (2926.1)	153251.5*** (3065.9)	14.33*** (0.307)
Very shallow Entisols	-44089.1*** (2926.1)	-46479.2*** (3064.1)	-4.278*** (0.307)
Very shallow inceptisols	-51584.6*** (5389.3)	-53705.2*** (5645.5)	-4.945*** (0.565)
Constant	157031.4*** (33887.9)	-152872.2*** (38107.4)	-4.850 (3.630)
Random-effects parameters			
Soil type	-4.558 (7.717)	-4.023 (7.745)	-13.95 (101.7)
Grid	9.016*** (0.0754)	9.061*** (0.0754)	-0.148* (0.0754)
Residual	9.998*** (0.00470)	10.06*** (0.00479)	0.857*** (0.00470)
Observations	22714	21881	22714

Appendix 2k: Mixed effects models explaining simulated outcome variables for the Soybean-Maize system (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo-transpiration in INR/m³
Year of cultivation	-394.7*** (15.97)	-378.5*** (18.20)	-0.0355*** (0.00164)
Management parameters			
manure in kg	-0.581** (0.226)	-0.739** (0.248)	-0.0000578* (0.0000231)
fertilizer in kg	40.23*** (6.331)	-11.27 (6.953)	0.00447*** (0.000648)
irrigation in mm	52.85*** (5.541)	63.93*** (6.088)	0.00532*** (0.000567)
Climate scenarios (reference are observed climate data over the past 30 years)			
Cool wet	-766.0* (346.2)	-1013.8** (380.4)	0.0181 (0.0354)
Hot dry	14733.2*** (344.4)	16286.0*** (378.4)	1.441*** (0.0353)
Soil types (reference are Slightly deep inceptisols)			
Deep Entisol	10717.7 (7285.4)	10722.9 (8444.6)	1.053 (0.745)
Deep Vertisol	45726.4*** (4151.1)	46184.3*** (4812.4)	4.689*** (0.424)
Extremly shallow Entisols	-46865.6*** (6137.6)	-52877.8*** (7114.6)	-4.682*** (0.628)
Slightly deep Entisols	-15157.6** (4748.7)	-18248.2*** (5502.3)	-1.641*** (0.486)
Shallow inceptisols	-6292.8 (4742.6)	-6137.0 (5496.9)	-0.570 (0.485)
Very Deep Inceptisols	4636.1 (6155.0)	5283.8 (7135.2)	0.340 (0.629)
Very Deep Vertisol	100732.9*** (3298.0)	103422.0*** (3823.1)	10.76*** (0.337)
Very shallow Entisols	-36735.8*** (3334.9)	-39867.6*** (3864.4)	-3.721*** (0.341)
Very shallow inceptisols	-39328.0*** (6147.8)	-43765.3*** (7126.9)	-4.012*** (0.629)
Constant	807536.4*** (32015.3)	750983.0*** (36477.4)	72.70*** (3.278)
Random-effects parameters			
Soil type	-0.177 (37.20)	-0.871 (6.909)	-16.71* (8.084)
Grid	9.156*** (0.0755)	9.305*** (0.0754)	-0.0324 (0.0755)
Residual	9.905*** (0.00486)	9.980*** (0.00495)	0.718*** (0.00486)
Observations	21259	20486	21259

Appendix 3a: OLS models explaining averages of simulated outcome variables over 30 simulated years for the Cotton-Fallow system; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1)	(2)	(3)	(4)
	Net profit in INR/ha	Total ESS value in INR/ha	Net profit by evapo - transpiration in INR/m^3	Total income (before costs) in INR/ha
Climate scenarios (reference are observed climate data over the past 30 years)				
Cool wet	-8181.5*** (1397.1)	-8309.7*** (1378.9)	-0.711*** (0.170)	0.752*** (0.172)
Hot dry	14042*** (1576.3)	14651*** (1572.1)	2.011*** (0.191)	-0.583*** (0.17)
Soil types (reference are Slightly deep inceptisols)				
Deep Entisol	55928.3*** (3419)	54933.0*** (3333)	5.542*** (0.602)	-0.492 (0.398)
Deep Vertisol	78179.8*** (2028)	74669.6*** (1987)	8.243*** (0.275)	-1.314*** (0.21)
Extremly shallow Entisols	-49315.6*** (2812)	-44721.7*** (2858)	-7.064*** (0.367)	26.43*** (0.371)
Slightly deep Entisols	2218.1 (3191.7)	3824.1 (3142.6)	-0.441 (0.566)	0.603 (0.536)
Shallow inceptisols	-16241.8*** (4343)	-16027.2*** (4389)	-1.918*** (0.487)	1.381 (0.722)
Very Deep Inceptisols	36917.3*** (4740)	34316.2*** (4615)	3.849*** (0.518)	0.694 (0.437)
Very Deep Vertisol	133257.5*** (1938)	127968.7*** (1940)	13.81*** (0.244)	-1.901*** (0.19)
Very shallow Entisols	-45440.6*** (1767)	-41263.3*** (1778)	-6.613*** (0.244)	25.81*** (0.354)
Very shallow inceptisols	-41838.2*** (2558)	-38542.6*** (2653)	-5.808*** (0.294)	22.69*** (0.687)
Agro-ecological zones (reference is Sub-humid (dry)				
Semi-arid (dry)	6386.4 (3436.6)	6810.2* (3411.4)	-0.218 (0.411)	0.129 (0.274)
Semi-arid (moist)	3775.4 (2893.6)	4470.7 (2890.9)	0.399 (0.307)	-0.0866 (0.073)
Sub-humid (moist)	8802.0 (7012.8)	7894.2 (6957.3)	0.284 (0.724)	-0.112 (0.181)
Management packages (reference is empirically observed farmers practice)				
75% recommended fertilizer, 3t FYM, less 1 irrigation than recommended	-733.3 (1964.9)	1436.9 (1943.0)	-0.194 (0.276)	0.809* (0.347)
75% recommended fertilizer, 2.25t FYM, recommended irrigation	632.5 (1927.7)	1829.3 (1906.0)	-0.0713 (0.273)	0.525 (0.345)
recommended fertilizer, 2.25t FYM, less 1 irrigation than recommended	-22098.1*** (2365)	-21141.2*** (2358)	-2.103*** (0.306)	0.777* (0.345)
recommended fertilizer, 3t FYM, recommended irrigation	1534.2 (1944.9)	2340.4 (1922.4)	0.0118 (0.273)	0.154 (0.353)
Constant	34045.9*** (3492)	5995.2 (3486.6)	4.190*** (0.422)	1.669*** (0.347)
Observations	779	779	779	779
Adjusted R^2	0.952	0.948	0.946	0.972

Appendix 3b: OLS models explaining averages of simulated outcome variables over 30 simulated years for the Maize-Chickpea system; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo - transpiration in INR/m³	(4) Total income (before costs) in INR/ha
Climate scenarios (reference are observed climate data over the past 30 years)				
Cool wet	4255.9** (1365.1)	3651.8* (1445.9)	0.236 (0.140)	-0.796** (0.259)
Hot dry	1021.2 (1504.2)	-209.3 (1609.8)	-0.329* (0.157)	0.341 (0.266)
Soil types (reference are Slightly deep inceptisols)				
Deep Entisol	54737.7*** (1689)	58194.9*** (1825)	5.504*** (0.164)	-3.934*** (0.62)
Deep Vertisol	59625.7*** (2302)	62272.6*** (2435)	6.027*** (0.229)	0.0284 (0.326)
Extremly shallow Entisols	-57054.4*** (1978)	-60715.6*** (2088)	-5.576*** (0.175)	15.44*** (1.396)
Slightly deep Entisols	-9602.7*** (1757.8)	-9664.5*** (1860.8)	-0.920*** (0.174)	-0.601 (0.512)
Shallow inceptisols	3586.2 (2071.8)	4728.0* (2126.7)	0.558** (0.191)	0.604 (0.315)
Very Deep Inceptisols	13423.0*** (2388)	15677.6*** (2425)	1.574*** (0.222)	0.562 (0.321)
Very Deep Vertisol	115772.0*** (1813)	122522.0*** (1882)	12.26*** (0.181)	0.647* (0.277)
Very shallow Entisols	-41339.1*** (1368)	-43280.9*** (1403)	-4.068*** (0.124)	6.314*** (0.551)
Very shallow inceptisols	-44157.3*** (1582)	-46817.3*** (1673)	-4.380*** (0.141)	6.041*** (0.800)
Agro-ecological zones (reference is Sub-humid (dry)				
Semi-arid (dry)	-23470.3*** (2271)	-26361.5*** (2420)	-2.815*** (0.234)	4.774*** (0.694)
Semi-arid (moist)	-14826.1*** (1677)	-16701.7*** (1786)	-1.944*** (0.180)	0.107 (0.0805)
Sub-humid (moist)	11439.1*** (2577)	11648.5*** (2735)	0.820** (0.259)	4.01e^{14} (0.167)
Management packages (reference is empirically observed farmers practice)				
75% recommended fertilizer, 3t FYM, less 1 irrigation than recommended	-1952.2 (2949.6)	119.9 (3108.3)	-0.209 (0.303)	0.394 (0.496)
75% recommended fertilizer, 2.25t FYM, recommended irrigation	3832.9 (2849.6)	6399.5* (3000.6)	0.373 (0.292)	-0.283 (0.470)
recommended fertilizer, 2.25t FYM, less 1 irrigation than recommended	-1096.6 (2951.8)	-505.5 (3108.7)	-0.126 (0.303)	0.355 (0.496)
recommended fertilizer, 3t FYM, recommended irrigation	4225.3 (2859.0)	4862.3 (3008.9)	0.410 (0.293)	-0.158 (0.476)
Constant	71030.1*** (3083.5)	37194.4*** (3234.7)	7.691*** (0.315)	-0.579 (0.501)
Observations	788	788	788	788
Adjusted R^2	0.949	0.949	0.951	0.649

Appendix 3c: OLS models explaining averages of simulated outcome variables over 30 simulated years for the Sorghum-fallow system; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo - transpiration in INR/m^3	(4) Total income (before costs) in INR/ha
Climate scenarios (reference are observed climate data over the past 30 years)				
Cool wet	-1313.5*** (244.1)	-1488.7*** (245.4)	-0.398*** (0.0586)	-0.174*** (0.05)
Hot dry	1497.5*** (242.4)	731.9** (251.7)	-0.151* (0.0602)	-0.113* (0.049)
Soil types (reference are Slightly deep inceptisols)				
Deep Entisol	1807.6 (1006.0)	2848.6** (1030.8)	1.048*** (0.244)	-0.264*** (0.08)
Deep Vertisol	28875.7*** (650.2)	28820.2*** (663.8)	5.715*** (0.158)	0.0550 (0.0580)
Extremly shallow Entisols	-39096.9*** (704.6)	-41790.2*** (772.3)	-7.958*** (0.163)	0.781*** (0.230)
Slightly deep Entisols	-949.1 (1709.7)	-948.4 (1670.5)	-0.0448 (0.375)	0.127 (0.0708)
Shallow inceptisols	-12704.2*** (689.7)	-13293.9*** (702.6)	-2.782*** (0.162)	0.0667 (0.0417)
Very Deep Inceptisols	-12854.1*** (800.0)	-13125.0*** (817.1)	-2.620*** (0.190)	0.0667 (0.0417)
Very Deep Vertisol	26796.0*** (681.8)	26602.9*** (687.3)	5.574*** (0.159)	0.0665* (0.031)
Very shallow Entisols	-32413.4*** (673.0)	-33698.6*** (681.2)	-6.611*** (0.156)	0.217*** (0.055)
Very shallow inceptisols	-38443.1*** (834.3)	-40321.0*** (857.0)	-7.817*** (0.182)	0.413*** (0.095)
Agro-ecological zones (reference is Sub-humid (dry)				
Semi-arid (dry)	3003.4*** (759.3)	2195.4** (743.5)	0.157 (0.162)	0.338*** (0.091)
Semi-arid (moist)	1877.3*** (532.2)	1407.2** (497.0)	0.0314 (0.105)	-0.0027 (0.022)
Management packages (reference is empirically observed farmers practice)				
75% recommended fertilizer, 3t FYM, less 1 irrigation than recommended	6232.7** (2002.2)	6587.9*** (1951.9)	1.363** (0.418)	0.268*** (0.071)
75% recommended fertilizer, 2.25t FYM, recommended irrigation	5274.1** (2002.0)	5628.5** (1952.3)	1.170** (0.418)	0.103* (0.0482)
recommended fertilizer, 2.25t FYM, less 1 irrigation than recommended	12155.2*** (2004.1)	12339.9*** (1953.1)	2.585*** (0.418)	0.238*** (0.066)
recommended fertilizer, 3t FYM, recommended irrigation	12382.6*** (2006.6)	12705.3*** (1956.3)	2.662*** (0.419)	0.101* (0.0482)
Constant	40759.9*** (2178)	23363.2*** (2126)	8.341*** (0.458)	-0.140** (0.051)
Observations	602	602	602	602
Adjusted R^2	0.972	0.974	0.969	0.254

Appendix 3d: OLS models explaining averages of simulated outcome variables over 30 simulated years for the Sorghum- Wheat system; (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo - transpiration in INR/m³	(4) Total income (before costs) in INR/ha
Climate scenarios (reference are observed climate data over the past 30 years)				
Cool wet	-5048.6*** (590.4)	-7796.3*** (655.4)	-0.898*** (0.0696)	0.0253 (0.128)
Hot dry	-5502.9*** (608.3)	-10232.8*** (676.8)	-1.254*** (0.0700)	0.402** (0.131)
Soil types (reference are Slightly deep inceptisols)				
Deep Entisol	13762.7*** (1344)	14087.5*** (1558)	1.214*** (0.146)	-0.868*** (0.26)
Deep Vertisol	30724.9*** (876.9)	29816.6*** (947.4)	2.475*** (0.0873)	0.0804 (0.104)
Extremly shallow Entisols	-72238.4*** (1433)	-79429.6*** (1539)	-6.093*** (0.146)	12.78*** (0.773)
Slightly deep Entisols	-2915.2 (2502.4)	-4335.9 (2545.1)	-0.363 (0.236)	0.0477 (0.154)
Shallow inceptisols	-18269.0*** (1483)	-20869.7*** (1482)	-1.825*** (0.134)	0.184 (0.154)
Very Deep Inceptisols	-6367.1 (4369.9)	-8686.8* (4304.3)	-0.849* (0.382)	0.0993 (0.175)
Very Deep Vertisol	35213.4*** (950.3)	33782.6*** (1023)	2.796*** (0.104)	0.214* (0.104)
Very shallow Entisols	-58556.3*** (917.0)	-63257.3*** (989.8)	-5.017*** (0.0928)	1.742*** (0.227)
Very shallow inceptisols	-68245.0*** (1534)	-73631.2*** (1737)	-5.740*** (0.151)	7.300*** (1.288)
Agro-ecological zones (reference is Sub-humid (dry)				
Semi-arid (dry)	-3296.3* (1605.2)	-4596.2** (1755.7)	-0.507** (0.179)	1.098*** (0.309)
Semi-arid (moist)	-3053.6* (1261.0)	-4491.4** (1406.1)	-0.560*** (0.155)	-0.0272 (0.051)
Sub-humid (moist)	-1439.2 (1694.2)	-3642.5 (1863.4)	-0.656** (0.201)	0.0415 (0.0837)
Management packages (reference is empirically observed farmers practice)				
75% recommended fertilizer, 3t FYM, less 1 irrigation than recommended	13090.0*** (3169)	13236.9*** (3074)	1.254*** (0.271)	-1.212* (0.546)
75% recommended fertilizer, 2.25t FYM, recommended irrigation	13026.0*** (3159)	13244.0*** (3062)	1.259*** (0.270)	-1.383* (0.543)
recommended fertilizer, 2.25t FYM, less 1 irrigation than recommended	25479.6*** (3201)	24776.0*** (3108)	2.289*** (0.275)	-1.482** (0.550)
recommended fertilizer, 3t FYM, recommended irrigation	26515.1*** (3183)	25998.6*** (3088)	2.394*** (0.273)	-1.644** (0.541)
Constant	63392.4*** (3306)	25248.2*** (3267)	5.837*** (0.302)	1.031 (0.531)
Observations	778	778	778	778
Adjusted R^2	0.959	0.957	0.938	0.709

Appendix 3e: OLS models explaining averages of simulated outcome variables over 30 simulated years for the Millet-Sorghum system; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo - transpiration in INR/m^3	(4) Total income (before costs) in INR/ha
Climate scenarios (reference are observed climate data over the past 30 years)				
Cool wet	1953.0* (827.3)	2750.7*** (829.0)	0.636*** (0.103)	-0.473 (0.317)
Hot dry	5425.5*** (857.2)	6223.7*** (855.7)	1.047*** (0.106)	-0.304 (0.326)
Soil types (reference are Slightly deep inceptisols)				
Deep Entisol	39824.5*** (2338)	39174.3*** (2400)	4.700*** (0.302)	-1.899*** (0.47)
Deep Vertisol	58249.2*** (1534)	58083.2*** (1561)	6.903*** (0.188)	0.223 (0.195)
Extremly shallow Entisols	-50139.8*** (1844)	-49816.0*** (1916)	-6.012*** (0.234)	25.61*** (0.533)
Slightly deep Entisols	-12470.1*** (1673)	-13018.9*** (1656)	-1.507*** (0.205)	0.330 (0.264)
Shallow inceptisols	8686.4*** (1736.7)	9276.0*** (1723.2)	1.208*** (0.202)	0.507 (0.280)
Very Deep Inceptisols	20911.3*** (2076)	21759.8*** (2148)	2.582*** (0.256)	0.500 (0.293)
Very Deep Vertisol	72084.6*** (1308)	72132.5*** (1300)	9.150*** (0.156)	0.546** (0.177)
Very shallow Entisols	-38985.8*** (1307)	-37834.0*** (1270)	-4.683*** (0.160)	11.41*** (0.724)
Very shallow inceptisols	-40439.6*** (1520)	-40184.2*** (1563)	-4.838*** (0.193)	13.54*** (0.909)
Agro-ecological zones (reference is Sub-humid (dry)				
Semi-arid (dry)	-901.4 (1755.2)	-1159.2 (1783.1)	-0.180 (0.220)	2.313*** (0.496)
Semi-arid (moist)	316.1 (1342.0)	308.8 (1353.9)	0.0341 (0.168)	-0.0859 (0.096)
Sub-humid (moist)	3288.0 (2760.8)	2859.8 (2707.9)	0.0974 (0.311)	0.0933 (0.132)
Management packages (reference is empirically observed farmers practice)				
75% recommended fertilizer, 3t FYM, less 1 irrigation than recommended	10339.4*** (2608)	9662.4*** (2712.6)	1.283*** (0.347)	-2.267** (0.787)
75% recommended fertilizer, 2.25t FYM, recommended irrigation	11016.2*** (2589)	10537.0*** (2692)	1.355*** (0.345)	-2.896*** (0.79)
recommended fertilizer, 2.25t FYM, less 1 irrigation than recommended	17527.1*** (2628)	16176.1*** (2731)	2.184*** (0.350)	-2.534** (0.790)
recommended fertilizer, 3t FYM, recommended irrigation	21316.9*** (2691)	19910.5*** (2796)	2.634*** (0.356)	-3.019*** (0.79)
Constant	25149.3*** (2799)	-4211.0 (2876.8)	2.715*** (0.364)	2.298** (0.727)
Observations	769	769	769	769
Adjusted R^2	0.961	0.960	0.960	0.759

Appendix 3f: OLS models explaining averages of simulated outcome variables over 30 simulated years for the Mungbean-Sorghum system; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo - transpiration in INR/m³	(4) Total income (before costs) in INR/ha
Climate scenarios (reference are observed climate data over the past 30 years)				
Cool wet	-2180.2* (1088.1)	-1522.0 (1113.4)	0.0683 (0.125)	-0.0312 (0.080)
Hot dry	24634.6*** (1106)	25526.0*** (1132)	3.019*** (0.126)	-0.0334 (0.077)
Soil types (reference are Slightly deep inceptisols)				
Deep Entisol	29217.3*** (2249)	27200.6*** (2635)	3.201*** (0.320)	-0.543*** (0.12)
Deep Vertisol	57039.9*** (2179)	56310.3*** (2226)	6.680*** (0.252)	0.132* (0.0547)
Extremly shallow Entisols	-71129.2*** (3036)	-71998.2*** (3138)	-8.146*** (0.357)	3.006** (0.912)
Slightly deep Entisols	-19881.4*** (1714)	-20967.9*** (1694)	-2.507*** (0.170)	0.297*** (0.09)
Shallow inceptisols	-6268.6** (1947.3)	-6338.7*** (1904.5)	-0.440* (0.206)	0.111 (0.0585)
Very Deep Inceptisols	8714.2*** (2311.7)	8342.0*** (2377.4)	0.943*** (0.280)	0.173***(0.0518)
Very Deep Vertisol	69735.8*** (1681)	69262.7*** (1672)	8.975*** (0.179)	0.170*** (0.049)
Very shallow Entisols	-53883.7*** (1605)	-53734.1*** (1603)	-6.091*** (0.176)	0.185***(0.0487)
Very shallow inceptisols	-53844.3*** (2170)	-53844.8*** (2291)	-6.113*** (0.263)	0.248*** (0.072)
Agro-ecological zones (reference is Sub-humid (dry)				
Semi-arid (dry)	-970.9 (2044.9)	-1313.4 (2070.3)	-0.224 (0.232)	0.708*** (0.160)
Semi-arid (moist)	981.2 (1413.0)	897.8 (1420.5)	0.0614 (0.160)	-0.0052 (0.013)
Sub-humid (moist)	4376.7 (2919.1)	3480.5 (2947.6)	-0.121 (0.332)	-0.004 (0.0283)
Management packages (reference is empirically observed farmers practice)				
75% recommended fertilizer, 3t FYM, less 1 irrigation than recommended	12138.6*** (2673)	11919.6*** (2734)	1.584*** (0.325)	0.0619 (0.0939)
75% recommended fertilizer, 2.25t FYM, recommended irrigation	10717.1*** (2616)	10556.8*** (2678)	1.415*** (0.318)	-0.0667 (0.083)
recommended fertilizer, 2.25t FYM, less 1 irrigation than recommended	15701.3*** (2716)	14850.7*** (2781)	2.012*** (0.330)	0.160 (0.129)
recommended fertilizer, 3t FYM, recommended irrigation	17568.3*** (2654)	16787.1*** (2716)	2.232*** (0.323)	-0.0625 (0.083)
Constant	72017.8*** (3173)	44550.4*** (3214)	8.055*** (0.374)	-0.167 (0.0904)
Observations	885	885	885	885
Adjusted R^2	0.939	0.936	0.945	0.304

Appendix 3g: OLS models explaining averages of simulated outcome variables over 30 simulated years for the Pigeonpea-Fallow system; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo - transpiration in INR/m³	(4) Total income (before costs) in INR/ha
Climate scenarios (reference are observed climate data over the past 30 years)				
Cool wet	6205.9*** (927.4)	6582.0*** (977.3)	1.335*** (0.187)	-0.330** (0.101)
Hot dry	7344.4*** (731.0)	8334.8*** (781.7)	1.691*** (0.148)	-0.0278 (0.107)
Soil types (reference are Slightly deep inceptisols)				
Deep Entisol	7265.7*** (1875.5)	8520.3*** (1975.0)	1.962*** (0.393)	-1.249*** (0.22)
Deep Vertisol	14615.1*** (1497)	13878.9*** (1568)	2.897*** (0.281)	0.146 (0.161)
Extremly shallow Entisols	-52807.7*** (2025)	-55101.2*** (2278)	-12.18*** (0.448)	3.075*** (0.750)
Slightly deep Entisols	-9069.1*** (1421.8)	-8704.4*** (1487.9)	-1.827*** (0.330)	0.0989 (0.166)
Shallow inceptisols	-267.5 (963.6)	948.7 (1002.7)	-0.0503 (0.186)	-0.00833 (0.12)
Very Deep Inceptisols	7548.5*** (1563.6)	9272.6*** (1671.4)	1.854*** (0.274)	-0.00623 (0.11)
Very Deep Vertisol	14467.4*** (1071)	13987.4*** (1104)	3.411*** (0.198)	-0.0032 (0.092)
Very shallow Entisols	-35266.0*** (1270)	-35416.0*** (1338)	-8.071*** (0.264)	0.479*** (0.137)
Very shallow inceptisols	-37770.1*** (1745)	-38236.7*** (1824)	-8.979*** (0.359)	0.361* (0.161)
Agro-ecological zones (reference is Sub-humid (dry)				
Semi-arid (dry)	-7992.2*** (1528.0)	-9751.5*** (1636.4)	-1.772*** (0.314)	1.278*** (0.241)
Semi-arid (moist)	398.7 (974.4)	32.80 (1010.6)	-0.0473 (0.193)	0.0138 (0.0368)
Sub-humid (moist)	1375.3 (1891.3)	1661.5 (2023.1)	-0.0515 (0.411)	0.0318 (0.0771)
Management packages (reference is empirically observed farmers practice)				
75% recommended fertilizer, 3t FYM, less 1 irrigation than recommended	-2712.7* (1322.1)	-119.1 (1305.7)	-0.706** (0.267)	0.299 (0.191)
75% recommended fertilizer, 2.25t FYM, recommended irrigation	84.16 (1284.7)	3201.8* (1256.6)	-0.0926 (0.258)	-0.130 (0.164)
recommended fertilizer, 2.25t FYM, less 1 irrigation than recommended	-2425.2 (1331.0)	-156.4 (1316.0)	-0.613* (0.269)	0.305 (0.191)
recommended fertilizer, 3t FYM, recommended irrigation	-768.7 (1286.0)	1899.8 (1257.9)	-0.233 (0.259)	-0.104 (0.164)
Constant	77958.2*** (1715)	66072.4*** (1701)	17.77*** (0.340)	-0.00399 (0.19)
Observations	721	721	721	721
Adjusted R^2	0.869	0.860	0.894	0.366

Appendix 3h: OLS models explaining averages of simulated outcome variables over 30 simulated years for the Rice-Chickpea system; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo - transpiration in INR/m³	(4) Total income (before costs) in INR/ha
Climate scenarios (reference are observed climate data over the past 30 years)				
Cool wet	-9549.5*** (708.6)	-12941.1*** (815.0)	-1.297*** (0.0744)	0.238 (0.128)
Hot dry	18917.9*** (653.6)	14472.5*** (819.3)	0.589*** (0.0614)	0.0579 (0.0990)
Soil types (reference are Slightly deep inceptisols)				
Deep Entisol	48325.5*** (852.4)	41566.5*** (1145)	3.000*** (0.108)	-0.549** (0.212)
Deep Vertisol	77285.3*** (763.2)	81869.7*** (815.2)	6.998*** (0.0716)	0.0143 (0.0483)
Extremly shallow Entisols	-52727.2*** (2231)	-66572.5*** (2422)	-4.665*** (0.151)	13.61*** (1.273)
Slightly deep Entisols	-10609.5*** (1550)	-23847.4*** (2641)	-1.680*** (0.171)	-0.194 (0.115)
Shallow inceptisols	3298.4** (1157.6)	4150.4** (1273.6)	0.348** (0.117)	0.181* (0.0842)
Very Deep Inceptisols	11767.7*** (950.3)	12793.7*** (1177)	1.084*** (0.0874)	0.181* (0.0842)
Very Deep Vertisol	125744.3*** (885)	133324.6*** (971)	11.43*** (0.0840)	0.181* (0.0730)
Very shallow Entisols	-31128.0*** (790.2)	-45739.0*** (1085)	-3.144*** (0.0732)	0.245*** (0.067)
Very shallow inceptisols	-36387.1*** (1763)	-50802.3*** (2316)	-3.472*** (0.136)	1.219** (0.380)
Agro-ecological zones (reference is Sub-humid (dry)				
Semi-arid (dry)	-4598.6** (1507.4)	-4805.6** (1813.1)	-0.873*** (0.178)	0.748** (0.275)
Semi-arid (moist)	-6412.6*** (1277.1)	-7890.7*** (1502.9)	-1.056*** (0.165)	-5.53e^{15} (0.022)
Sub-humid (moist)	3837.4 (2613.1)	3345.8 (2956.5)	-0.0669 (0.225)	6.15e^{15} (0.047)
Management packages (reference is empirically observed farmers practice)				
75% recommended fertilizer, 3t FYM, less 1 irrigation than recommended	-3434.0*** (866.5)	-2456.1* (1131.1)	-0.327** (0.102)	0.362 (0.262)
75% recommended fertilizer, 2.25t FYM, recommended irrigation	-3169.7*** (865.7)	-2152.6 (1130.0)	-0.302** (0.102)	0.340 (0.259)
recommended fertilizer, 2.25t FYM, less 1 irrigation than recommended	2755.5** (867.9)	2318.2* (1133.4)	0.199 (0.103)	0.233 (0.256)
recommended fertilizer, 3t FYM, recommended irrigation	2394.0** (868.1)	2066.4 (1135.2)	0.170 (0.103)	0.246 (0.257)
Constant	56938.3*** (1559)	22496.4*** (1852)	6.039*** (0.190)	-0.544* (0.229)
Observations	789	789	789	789
Adjusted R^2	0.987	0.985	0.985	0.787

Appendix 3i: OLS model explaining averages of simulated outcome variables over 30 simulated years for the Soybean-Chickpea system; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo - transpiration in INR/m^3	(4) Total income (before costs) in INR/ha
Climate scenarios (reference are observed climate data over the past 30 years)				
Cool wet	3143.3* (1368.0)	2106.6 (1507.6)	-0.0229 (0.155)	-0.607* (0.280)
Hot dry	19504*** (1632.7)	18954*** (2095.8)	1.237*** (0.182)	-0.696** (0.266)
Soil types (reference are Slightly deep inceptisols)				
Deep Entisol	58817*** (1506.9)	64063.9*** (1815)	6.725*** (0.160)	-5.356*** (0.71)
Deep Vertisol	61854.4*** (2302)	65304.9*** (2702)	6.815*** (0.249)	-0.697 (0.401)
Extremly shallow Entisols	-38470.6*** (1983)	-41841.8*** (2360)	-4.014*** (0.155)	16.76*** (1.213)
Slightly deep Entisols	-6614.8*** (1266.0)	-7953.2*** (1609.9)	-0.814*** (0.131)	0.258 (0.518)
Shallow inceptisols	8416.2*** (1298.2)	11693.4*** (1512)	1.039*** (0.129)	-0.0232 (0.353)
Very Deep Inceptisols	17112.6*** (1595)	19409.5*** (2016)	1.929*** (0.169)	0.0151 (0.349)
Very Deep Vertisol	120119.3*** (1839)	126333.3*** (2105)	13.49*** (0.202)	0.135 (0.327)
Very shallow Entisols	-26785.2*** (1221)	-27871.4*** (1452)	-2.848*** (0.112)	6.725*** (0.596)
Very shallow inceptisols	-27518.9*** (1720)	-27174.2*** (1860)	-2.879*** (0.141)	4.931*** (0.573)
Agro-ecological zones (reference is Sub-humid (dry)				
Semi-arid (dry)	-25415.9*** (2446)	-29096.5*** (2845)	-3.317*** (0.279)	5.558*** (0.789)
Semi-arid (moist)	-14867.3*** (2001)	-16656.9*** (2294)	-2.193*** (0.240)	0.120 (0.0701)
Sub-humid (moist)	8510.3* (3647.4)	8283.4* (4135.3)	0.372 (0.365)	-6.87e^{14} (0.140)
Management packages (reference is empirically observed farmers practice)				
75% recommended fertilizer, 3t FYM, less 1 irrigation than recommended	-1423.3 (2945.0)	28.21 (3271.6)	-0.139 (0.337)	0.554 (0.496)
75% recommended fertilizer, 2.25t FYM, recommended irrigation	3888.9 (2840.4)	5559.9 (3169.6)	0.432 (0.325)	-0.271 (0.468)
recommended fertilizer, 2.25t FYM, less 1 irrigation than recommended	-1096.3 (2937.0)	-790.1 (3263.4)	-0.102 (0.336)	0.448 (0.491)
recommended fertilizer, 3t FYM, recommended irrigation	3068.2 (2842.4)	4171.4 (3161.1)	0.341 (0.325)	-0.110 (0.471)
Constant	44054.1*** (3158)	19826.3*** (3533)	5.622*** (0.361)	0.123 (0.524)
Observations	769	707	769	769
Adjusted R^2	0.942	0.936	0.942	0.700

Appendix 3j: OLS models explaining averages of simulated outcome variables over 30 simulated years for the Sorghum- Chickpea system; (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	(1) Net profit in INR/ha	(2) Total ESS value in INR/ha	(3) Net profit by evapo - transpiration in INR/m^3	(4) Total income (before costs) in INR/ha
Climate scenarios (reference are observed climate data over the past 30 years)				
Cool wet	3683.7*** (881.2)	2007.2* (926.4)	-0.0908 (0.0889)	-0.295*** (0.09)
Hot dry	12110.1*** (1107)	10247.8*** (1173)	0.291** (0.107)	-0.126 (0.103)
Soil types (reference are Slightly deep inceptisols)				
Deep Entisol	55719.8*** (1133)	61412.4*** (1158)	6.126*** (0.0972)	-1.001*** (0.19)
Deep Vertisol	82071.9*** (1457)	86211.5*** (1507)	7.989*** (0.135)	0.0228 (0.0963)
Extremly shallow Entisols	-55884.8*** (1441)	-59620.0*** (1539)	-5.363*** (0.0978)	9.487*** (0.820)
Slightly deep Entisols	-870.0 (1900.6)	-818.8 (1863.9)	-0.0349 (0.169)	0.602* (0.258)
Shallow inceptisols	-3100.1* (1341.7)	-2596.3 (1439.9)	-0.312** (0.0980)	0.129 (0.102)
Very Deep Inceptisols	14483.1*** (2782)	15771.2*** (2575)	1.384*** (0.253)	0.109 (0.102)
Very Deep Vertisol	137233.9*** (1237)	144425.5*** (1278)	13.49*** (0.119)	0.129 (0.0843)
Very shallow Entisols	-42449.2*** (866.2)	-45808.5*** (873.3)	-4.163*** (0.0675)	0.703*** (0.120)
Very shallow inceptisols	-50755.3*** (1267)	-53102.5*** (1361)	-4.900*** (0.0906)	2.402*** (0.341)
Agro-ecological zones (reference is Sub-humid (dry)				
Semi-arid (dry)	-10988.7*** (1774)	-12905.2*** (1902)	-1.601*** (0.187)	1.130*** (0.221)
Semi-arid (moist)	-10185.7*** (1490)	-11548.8*** (1616)	-1.459*** (0.167)	-4.50e^{14} (0.030)
Sub-humid (moist)	6729.9* (2606.6)	6432.4* (2823.5)	0.166 (0.222)	-5.56e^{14} (0.064)
Management packages (reference is empirically observed farmers practice)				
75% recommended fertilizer, 3t FYM, less 1 irrigation than recommended	3534.7 (2288.0)	4447.6 (2327.3)	0.416 (0.219)	0.0678 (0.174)
75% recommended fertilizer, 2.25t FYM, recommended irrigation	5419.7* (2231.1)	6522.1** (2267.3)	0.593** (0.213)	-0.249 (0.155)
recommended fertilizer, 2.25t FYM, less 1 irrigation than recommended	10682.2*** (2304)	11093.3*** (2345)	1.141*** (0.221)	-0.0996 (0.188)
recommended fertilizer, 3t FYM, recommended irrigation	14016.1*** (2233)	14729.1*** (2269)	1.464*** (0.214)	-0.358* (0.161)
Constant	57751.4*** (2598)	25921.4*** (2663)	6.347*** (0.261)	0.148 (0.165)
Observations	796	796	796	796
Adjusted R^2	0.978	0.978	0.979	0.759

Appendix 3k: OLS models explaining averages of simulated outcome variables over 30 simulated years for the Soybean-Maize system; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1)	(2)	(3)	(4)
	Net profit in INR/ha	Total ESS value in INR/ha	Net profit by evapo - transpiration in INR/m³	Total income (before costs) in INR/ha
Climate scenarios (reference are observed climate data over the past 30 years)				
Cool wet	149.4 (1084.9)	15.47 (1192.5)	0.111 (0.111)	-0.554* (0.276)
Hot dry	14753.2*** (1211)	16195.8*** (1332)	1.445*** (0.125)	-1.226*** (0.28)
Soil types (reference are Slightly deep inceptisols)				
Deep Entisol	17555.6*** (1663)	17318.8*** (1833)	1.746*** (0.159)	-3.731*** (0.69)
Deep Vertisol	49319.9*** (2291)	49930.7*** (2551)	5.044*** (0.234)	-1.029* (0.417)
Extremly shallow Entisols	-46826.7*** (1914)	-53059.2*** (2278)	-4.654*** (0.177)	19.04*** (1.155)
Slightly deep Entisols	-12413.6*** (1399)	-14951.5*** (1482)	-1.346*** (0.134)	0.692 (0.553)
Shallow inceptisols	6009.4* (2529.0)	8226.3** (2777.7)	0.742** (0.273)	-0.192 (0.361)
Very Deep Inceptisols	8163.0** (2930.5)	8840.4** (3236.5)	0.717* (0.280)	-0.192 (0.361)
Very Deep Vertisol	98039.2*** (1581)	100293.2*** (1724)	10.48*** (0.156)	-0.153 (0.326)
Very shallow Entisols	-35548.3*** (1339)	-39293.1*** (1507)	-3.616*** (0.128)	9.860*** (0.566)
Very shallow inceptisols	-37494.9*** (1674)	-41297.0*** (1892)	-3.825*** (0.160)	11.65*** (0.978)
Agro-ecological zones (reference is Sub-humid (dry)				
Semi-arid (dry)	-16674.3*** (1953)	-18815.1*** (2149)	-1.818*** (0.203)	5.040*** (0.726)
Semi-arid (moist)	-7508.3*** (1374.7)	-8026.2*** (1481.3)	-0.910*** (0.149)	0.0385 (0.0816)
Sub-humid (moist)	4159.8 (2293.6)	3697.1 (2511.7)	-0.0739 (0.241)	-1.70e^{13} (0.175)
Management packages (reference is empirically observed farmers practice)				
75% recommended fertilizer, 3t FYM, less 1 irrigation than recommended	-4016.6 (2442.0)	-2638.3 (2693.4)	-0.421 (0.255)	0.592 (0.524)
75% recommended fertilizer, 2.25t FYM, recommended irrigation	-957.4 (2381.0)	1005.7 (2628.1)	-0.113 (0.249)	-0.119 (0.503)
recommended fertilizer, 2.25t FYM, less 1 irrigation than recommended	-1041.7 (2495.3)	-1685.6 (2742.9)	-0.104 (0.261)	0.533 (0.522)
recommended fertilizer, 3t FYM, recommended irrigation	1503.7 (2425.2)	1330.4 (2664.5)	0.153 (0.254)	0.0812 (0.506)
Constant	45311.9*** (2721)	15562.6*** (2989)	4.729*** (0.280)	0.450 (0.560)
Observations	760	760	760	760
Adjusted R^2	0.958	0.953	0.960	0.786

Appendix 4a: Mixed effects models explaining simulated net profit in INR/ha across climate scenarios (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	historic climate		wet cool scenario		hot dry scenario	
	coef.	rank	coef.	rank	coef.	rank
Management Parameters						
manure in kg	2.057*** (0.0651)		0.819*** (0.170)		1.443*** (0.207)	
fertilizer application in kg	162.1*** (2.937)		145.2*** (4.419)		121.3*** (5.412)	
irrigation in mm	4.415*** (1.191)		-13.28*** (1.260)		-9.152*** (1.477)	
Climate variables						
Average minimum temperature in °C	2191.1*** (153.6)		2566.8*** (161.1)		2012.1*** (194.1)	
August rainfall in mm	11.12*** (0.600)		1.322* (0.639)		12.97*** (0.780)	
Number of annual rainy days	253.4*** (6.253)		7.373 (6.661)		244.1*** (8.082)	
Consecutive dry days during monsoon	29.16* (14.37)		39.28* (15.26)		45.77* (18.56)	
solar radiation	4384.0*** (119.0)		3975.4*** (126.2)		4957.2*** (153.4)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	27444*** (3176)	7	21333*** (3181)	10	36461.6*** (3506)	7
Maize-Chickpea	41740*** (3175.9)	4	47922.2*** (3184)	4	39896.7*** (3511)	6
Sorghum-Fallow	22646.5*** (3179)	9	22698.7*** (3199)	8	19592.9*** (3526)	11
Sorghum-Wheat	26718.7*** (3173)	8	29181.4*** (3188)	7	25385.9*** (3516)	9
Millet-Sorghum	14445.8*** (3168)	10	22176.6*** (3176)	9	21371.1*** (3499)	10
Mungbean- Sorghum	56316.3*** (3166)	2	60215.7*** (3171)	2	81131.9*** (3490)	1
Pigeonpea-Fallow	45709.7*** (3179)	3	52672.9*** (3189)	3	46904.7*** (3514)	4
Rice-Chickpea	38645.3*** (3271)	5	47306.8*** (3276)	5	65239.9*** (3633)	2
Soybean-Chickpea	30933.3*** (3172)	6	35180.3*** (3176)	6	44398.5*** (3499)	5
Sorghum- Chickpea	58176.2*** (3171)	1	63435.9*** (3175)	1	64558.5*** (3499)	3
Soybean-Maize	9475.0** (3176)	11	16859.4*** (3189)	11	27457.7*** (3516)	8
Soil types (reference are Slightly deep inceptisols)						
Deep Entisol	27021.0*** (5322.6)		25722.4*** (5330.3)		27698.3*** (5867.3)	
Deep Vertisol	37094.0*** (3037.6)		39192.3*** (3041.4)		40041.5*** (3348.6)	
Extremly shallow Entisols	-49937.0*** (4491.7)		-48349.3*** (4498.1)		-61201.2*** (4954.9)	
Slightly deep Entisols	-5684.3 (3462.8)		-7315.6* (3468.1)		-7468.8 (3820.1)	
Shallow inceptisols	-11285.4** (3463.0)		-11204.1** (3468.3)		-13539.6*** (3820.3)	
Very Deep Inceptisols	-3616.9 (4500.4)		-5723.5 (4508.4)		-5415.9 (4967.4)	
Very Deep Vertisol	58680.8*** (2433.8)		56062.3*** (2439.7)		58467.8*** (2690.5)	
Very shallow Entisols	-36035.0*** (2435.2)		-33069.5*** (2439.1)		-43555.2*** (2687.3)	
Very shallow inceptisols	-43177.7*** (4495.6)		-40805.7*** (4502.6)		-51153.7*** (4961.1)	
Constant	-141828.9*** (4150.2)		-125707.3*** (4334.4)		-137562.4*** (5093.2)	
Random-effects parameters						
Grid	-3.255 (2.199)		-3.797 (2.623)		-2.022 (2.559)	
Cropping System	10.20*** (0.0194)		10.21*** (0.0193)		10.30*** (0.0193)	
Residual	9.917*** (0.00231)		9.871*** (0.00234)		10.09*** (0.00231)	
Observations	114497		92437		95958	

Appendix 4b: Mixed effects models explaining simulated total ecosystem service value in INR/ha across climate scenarios (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	historic climate		wet cool scenario		hot dry scenario	
	coef.	rank	coef.	rank	coef.	rank
Management Parameters						
manure in kg	2.054*** (0.0681)		0.817*** (0.175)		2.034*** (0.218)	
fertilizer application in kg	129.0*** (3.061)		106.4*** (4.552)		86.02*** (5.666)	
irrigation in mm	42.08*** (1.824)		-1.467 (1.823)		19.55*** (2.191)	
Climate variables						
Average minimum temperature in °C	1885.3*** (160.0)		2271.3*** (165.6)		1718.2*** (202.6)	
August rainfall in mm	9.322*** (0.632)		-2.990*** (0.665)		10.97*** (0.826)	
Number of annual rainy days	317.8*** (6.495)		74.04*** (6.829)		312.9*** (8.440)	
Consecutive dry days during monsoon	84.57*** (15.01)		103.2*** (15.73)		106.7*** (19.49)	
solar radiation	3411.2*** (123.0)		2791.3*** (128.7)		3943.5*** (159.4)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	22165.6*** (3517)	7	11661.0*** (3342)	8	29015.9*** (3736)	5
Maize-Chickpea	29310.8*** (3514)	4	31669.0*** (3343)	4	24521.7*** (3739)	6
Sorghum-Fallow	24460.5*** (3522)	6	19084.3*** (3361)	6	18242.3*** (3759)	8
Sorghum-Wheat	578.1 (3506.5)		890.6 (3342.5)		-5701.2 (3737.3)	
Millet-Sorghum	-1053.5 (3501.6)		7762.7* (3330.3)	9	6016.6 (3720.1)	
Mungbean- Sorghum	41368.1*** (3500)	3	46386.0*** (3325)	2	66827.8*** (3711)	1
Pigeonpea-Fallow	54987.7*** (3521)	1	56916.4*** (3350)	1	54572.4*** (3745)	2
Rice-Chickpea	-8729.5* (3704.6)	11	14061.6*** (3514)	7	18509.5*** (3973)	7
Soybean-Chickpea	25967.0*** (3510)	5	25592.9*** (3333)	5	35400.3*** (3732)	4
Sorghum- Chickpea	45712.9*** (3509)	2	45666.1*** (3333)	3	48073.7*** (3725)	3
Soybean-Maize	-5012.7 (3508.9)		2555.6 (3343.0)		13619.4*** (3738)	9
Soil types (reference are Slightly deep inceptisols)						
Deep Entisol	29060.5*** (5883.1)		26747.3*** (5589.8)		30094.9*** (6239.6)	
Deep Vertisol	38640.6*** (3357.4)		40277.9*** (3189.3)		41772.5*** (3561.0)	
Extremly shallow Entisols	-50787.4*** (4964.0)		-49759.1*** (4716.7)		-63313.1*** (5268.8)	
Slightly deep Entisols	-4242.6 (3827.2)		-8120.2* (3637.0)		-7205.4 (4062.8)	
Shallow inceptisols	-11321.9** (3827.0)		-11352.3** (3636.9)		-13390.8*** (4062.6)	
Very Deep Inceptisols	-1574.1 (4973.0)		-4665.6 (4727.7)		-3994.6 (5282.5)	
Very Deep Vertisol	63144.6*** (2688.7)		58606.7*** (2558.3)		62575.6*** (2861.1)	
Very shallow Entisols	-36057.1*** (2691.0)		-33872.9*** (2557.7)		-44437.0*** (2857.7)	
Very shallow inceptisols	-43412.7*** (4968.1)		-41979.1*** (4721.6)		-52769.8*** (5275.8)	
Constant	-140607.5*** (4456.1)		-113264.3*** (4528.2)		-134345.6*** (5397.9)	
Random-effects parameters						
Grid	-1.476 (2.194)		-1.745 (2.044)		-1.773 (2.253)	
Cropping System	10.31*** (0.0201)		10.25*** (0.0193)		10.36*** (0.0201)	
Residual	9.940*** (0.00217)		9.881*** (0.00239)		10.11*** (0.00254)	
Observations	110439		89173		90944	

Appendix 4c: Mixed effects models explaining simulated net profit per unit evapo-transpiration in INR/m^3 across climate scenarios (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	historic climate		wet cool scenario		hot dry scenario	
	coef.	rank	coef.	rank	coef.	rank
Management Parameters						
manure in kg	0.000230*** (0.00000895)		0.0000513* (0.0000217)		0.000107*** (0.0000267)	
fertilizer application in kg	0.0200*** (0.000403)		0.0175*** (0.000563)		0.0144*** (0.000696)	
irrigation in mm	0.000596*** (0.000159)		-0.00149*** (0.000158)		-0.000771*** (0.000186)	
Climate variables						
Average minimum temperature in ^{o}C	0.224*** (0.0209)		0.275*** (0.0204)		0.214*** (0.0247)	
August rainfall in mm	0.00155*** (0.0000824)		0.000190* (0.0000816)		0.00166*** (0.000100)	
Number of annual rainy days	0.0388*** (0.000859)		0.0107*** (0.000850)		0.0424*** (0.00104)	
Consecutive dry days during monsoon	0.00601** (0.00197)		0.00748*** (0.00195)		0.00937*** (0.00239)	
solar radiation	0.223*** (0.0163)		0.167*** (0.0161)		0.192*** (0.0198)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	-1.705*** (0.345)	8	-1.722*** (0.342)	9	-0.303 (0.372)	
Maize-Chickpea	-0.242 (0.345)		0.824* (0.343)	5	-0.728 (0.373)	
Sorghum-Fallow	2.648*** (0.346)	2	3.025*** (0.344)	3	2.076*** (0.375)	3
Sorghum-Wheat	-3.042*** (0.345)	10	-2.518*** (0.343)	11	-3.757*** (0.374)	11
Millet-Sorghum	-2.289*** (0.344)	9	-0.529 (0.342)	8	-1.147** (0.371)	9
Mungbean- Sorghum	2.605*** (0.343)	3	3.845*** (0.341)	2	5.599*** (0.370)	2
Pigeonpea-Fallow	8.968*** (0.346)	1	10.83*** (0.343)	1	9.777*** (0.373)	1
Rice-Chickpea	-1.620*** (0.361)	7	-0.153 (0.356)		-0.00592 (0.391)	
Soybean-Chickpea	-0.523 (0.344)		0.206 (0.341)		0.241 (0.371)	
Sorghum- Chickpea	1.389*** (0.344)	4	2.104*** (0.341)	4	1.254*** (0.371)	4
Soybean-Maize	-3.681*** (0.345)	11	-2.213*** (0.343)	10	-1.846*** (0.374)	10
Soil types (reference are Slightly deep inceptisols)						
Deep Entisol	2.734*** (0.577)		2.539*** (0.573)		2.947*** (0.622)	
Deep Vertisol	4.327*** (0.329)		4.468*** (0.327)		4.539*** (0.355)	
Extremly shallow Entisols	-6.958*** (0.488)		-6.690*** (0.484)		-8.389*** (0.525)	
Slightly deep Entisols	-0.828* (0.376)		-1.021** (0.373)		-1.051** (0.405)	
Shallow inceptisols	-1.460*** (0.376)		-1.528*** (0.373)		-1.792*** (0.405)	
Very Deep Inceptisols	-0.683 (0.489)		-1.065* (0.485)		-1.109* (0.527)	
Very Deep Vertisol	6.543*** (0.265)		5.978*** (0.263)		6.051*** (0.286)	
Very shallow Entisols	-5.130*** (0.264)		-4.618*** (0.262)		-6.050*** (0.285)	
Very shallow inceptisols	-6.101*** (0.488)		-5.713*** (0.484)		-7.123*** (0.526)	
Constant	-6.518*** (0.533)		-4.962*** (0.528)		-4.290*** (0.626)	
Random-effects parameters						
Grid	-13.10*** (2.273)		-7.678 (47.61)		-14.33*** (2.742)	
Cropping System	1.073*** (0.0207)		1.065*** (0.0194)		1.146*** (0.0199)	
Residual	1.025*** (0.00213)		0.905*** (0.00234)		1.130*** (0.00231)	
Observations	114497		92437		95958	

Appendix 5a: OLS models explaining simulated net profit in INR/ha across climate scenarios (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	(1) historic climate coef.	rank	(2) wet cool scenario coef.	rank	(3) hot dry scenario coef.	rank
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	45854.4*** (7045.3)	5	41259.0*** (6576.7)	7	56876.4*** (7356)	5
Maize-Chickpea	59994.6*** (7053.2)	4	69382.9*** (6627.7)	2	58977.4*** (7359)	4
Sorghum-Fallow	17917.7* (6756.9)	11	22771.5** (6366.6)	11	19945.1* (7081.8)	11
Sorghum-Wheat	37512.8*** (6967.3)	7	40389.5*** (6625.9)	8	33058.6*** (7352)	9
Millet-Sorghum	22603.2** (6964.3)	10	32277.9*** (6607.9)	10	28660.4** (7345.8)	10
Mungbean-Sorghum	63716.7*** (7003.0)	2	69288.6*** (6575.5)	3	88479.2*** (7181)	1
Pigeonpea-Fallow	32266.2*** (6940.1)	8	46346.1*** (6400.9)	6	37255.5*** (7294)	8
Rice-Chickpea	61801.4*** (7051.2)	3	57285.3*** (6630.2)	4	78536.4*** (7366)	3
Soybean-Chickpea	38578.7*** (7035.2)	6	46932.3*** (6618.1)	5	55933.8*** (7340)	6
Sorghum-Chickpea	69090.7*** (7049.4)	1	79350.1*** (6617.1)	1	80642.7*** (7345)	2
Soybean-Maize	30847.4*** (7024.8)	9	35873.5*** (6595.7)	9	43100.7*** (7330)	7
Soil types (reference are Slightly deep inceptisols)						
Deep Entisol	27329.6*** (5579.9)		26300.3*** (6039.2)		28262.2*** (6087.9)	
Deep Vertisol	41802.3*** (6579.4)		45033.4*** (7456.1)		44526.7*** (7121.4)	
Extremly shallow Entisols	-43470.9*** (3763.2)		-44828.2*** (4223.2)		-54320.6*** (4899.8)	
Slightly deep Entisols	-5046.2* (1758.2)		-7397.6** (2343.2)		-8863.3*** (1914.8)	
Shallow inceptisols	-2135.4 (1987.8)		-3191.2 (2015.0)		-4694.4 (2765.1)	
Very Deep Inceptisols	7061.8 (4201.6)		3360.0 (3415.5)		9174.4* (3973.9)	
Very Deep Vertisol	68731.9*** (13195.5)		65312.0*** (13797.9)		68873.7*** (14552.5)	
Very shallow Entisols	-32562.8*** (3392.4)		-32116.8*** (3626.2)		-40325.2*** (4388.5)	
Very shallow inceptisols	-35739.5*** (3679.2)		-35416.1*** (4071.6)		-43362.1*** (4264.0)	
Agro-ecological zones (reference is Sub-humid (dry)						
Semi-arid (dry)	-14733.6*** (3528.3)		-9088.0** (2345.5)		-13374.7** (3289.4)	
Semi-arid (moist)	-10226.4** (2839.7)		-5968.6** (1594.3)		-10225.0** (2740.7)	
Sub-humid (moist)	16321.3* (5652.6)		11140.7* (5128.3)		19082.1** (6381.6)	
Constant	27261.8** (8395.1)		19354.9* (8689.5)		30745.2** (8309.9)	
Observations	4124		3288		3406	
Adjusted R^2	0.766		0.768		0.772	

Appendix 5b: OLS models explaining simulated Total ecosystem service value in INR/ha across climate scenarios (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	(1) historic climate coef.	rank	(2) wet cool scenario coef.	rank	(3) hot dry scenario coef.	rank
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	31014.9*** (5700.3)	6	26711.7*** (5461.0)	7	42300.5*** (6724)	5
Maize-Chickpea	41499.2*** (5710.2)	3	50561.6*** (5520.8)	3	38936.0*** (6725)	7
Sorghum-Fallow	13357.5* (5324.5)	9	18113.0** (5178.1)	9	14113.1* (6372.2)	9
Sorghum-Wheat	9171.7 (5597.0)		9256.3 (5519.7)		-644.8 (6718.6)	
Millet-Sorghum	5944.3 (5598.0)		16208.2* (5499.7)	10	11979.3 (6712.0)	
Mungbean-Sorghum	48655.3*** (5639.9)	2	54772.1*** (5449.9)	2	73580.3*** (6508)	1
Pigeonpea-Fallow	35023.3*** (5569.2)	5	50182.9*** (5233.0)	4	40952.2*** (6650)	6
Rice-Chickpea	39469.0*** (5706.5)	4	31658.2*** (5525.9)	6	51263.2*** (6735)	3
Soybean-Chickpea	29526.9*** (5692.2)	7	37090.1*** (5512.0)	5	45042.3*** (6707)	4
Sorghum-Chickpea	52778.1*** (5704.0)	1	61511.0*** (5507.3)	1	62009.6*** (6708)	2
Soybean-Maize	14174.6* (5680.0)	8	19199.2** (5484.6)	8	27436.3** (6692.6)	8
Soil types (reference are Slightly deep inceptisols)						
Deep Entisol	27613.7*** (5759.2)		26780.2*** (6169.1)		28705.9*** (6154.5)	
Deep Vertisol	42436.7*** (6836.2)		45555.2*** (7669.2)		44942.7*** (7534.8)	
Extremly shallow Entisols	-45827.4*** (4104.8)		-47847.0*** (4666.2)		-58358.1*** (5372.4)	
Slightly deep Entisols	-5698.7* (1971.4)		-8770.6** (2731.3)		-10490.8*** (2327.9)	
Shallow inceptisols	-1429.7 (2234.3)		-3015.1 (2277.2)		-4666.7 (2990.9)	
Very Deep Inceptisols	7491.5 (4125.9)		3467.9 (3471.4)		9403.7* (4190.4)	
Very Deep Vertisol	70485.2*** (13704.5)		66523.4*** (14305.8)		69411.9*** (15253.4)	
Very shallow Entisols	-33626.7*** (3580.6)		-34068.0*** (3942.7)		-43150.5*** (4628.5)	
Very shallow inceptisols	-37171.5*** (4001.0)		-37508.4*** (4476.3)		-46360.9*** (4649.4)	
Agro-ecological zones (reference is Sub-humid (dry)						
Semi-arid (dry)	-16275.7** (3935.2)		-10347.0** (2571.2)		-14895.4*** (3548.5)	
Semi-arid (moist)	-11135.8** (3131.9)		-6842.2** (1764.0)		-11119.9** (2981.6)	
Sub-humid (moist)	16221.8* (5879.8)		10720.8 (5340.7)		19241.7* (6798.4)	
Constant	14380.7 (7433.5)		6861.3 (7933.4)		19397.2* (7807.7)	
Observations	4124		3288		3344	
Adjusted R^2	0.741		0.740		0.743	

Appendix 5c: OLS models explaining simulated Net profit per unit evapotranspiration in INR/m^3 across climate scenarios (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) historic climate coef.	 rank	(2) wet cool scenario coef.	 rank	(3) hot dry scenario coef.	 rank
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	0.0519 (1.298)		0.292 (1.303)		1.732 (1.353)	
Maize-Chickpea	1.549 (1.298)		2.911* (1.308)	5	0.999 (1.353)	
Sorghum-Fallow	2.131 (1.266)		3.130* (1.285)	4	2.206 (1.330)	
Sorghum-Wheat	-2.130 (1.291)		-1.709 (1.309)		-3.388* (1.353)	11
Millet-Sorghum	-1.415 (1.289)		0.685 (1.307)		-0.242 (1.351)	
Mungbean-Sorghum	3.305* (1.298)	2	4.836** (1.310)	2	6.293*** (1.349)	2
Pigeonpea-Fallow	7.609*** (1.285)	1	10.12*** (1.292)	1	9.098*** (1.348)	1
Rice-Chickpea	0.591 (1.298)		0.416 (1.309)		0.936 (1.354)	
Soybean-Chickpea	0.200 (1.295)		1.321 (1.307)		1.214 (1.351)	
Sorghum-Chickpea	2.124 (1.298)		3.327* (1.308)		2.366 (1.352)	
Soybean-Maize	-1.494 (1.293)		-0.272 (1.304)		-0.317 (1.350)	
Soil types (reference are Slightly deep inceptisols)						
Deep Entisol	2.786*** (0.569)		2.602** (0.645)		3.000*** (0.621)	
Deep Vertisol	4.727*** (0.597)		4.941*** (0.719)		4.851*** (0.649)	
Extremly shallow Entisols	-6.356*** (0.613)		-6.425*** (0.618)		-7.716*** (0.671)	
Slightly deep Entisols	-0.826** (0.242)		-1.128** (0.287)		-1.457*** (0.279)	
Shallow inceptisols	-0.277 (0.289)		-0.494 (0.303)		-0.768* (0.356)	
Very Deep Inceptisols	0.649 (0.563)		0.0626 (0.465)		0.762 (0.572)	
Very Deep Vertisol	7.760*** (1.351)		7.010*** (1.436)		7.292*** (1.408)	
Very shallow Entisols	-4.643*** (0.471)		-4.485*** (0.438)		-5.677*** (0.575)	
Very shallow inceptisols	-5.104*** (0.509)		-4.979*** (0.497)		-6.056*** (0.537)	
Agro-ecological zones (reference is Sub-humid (dry)						
Semi-arid (dry)	-1.741*** (0.370)		-1.231*** (0.297)		-1.735*** (0.376)	
Semi-arid (moist)	-1.076** (0.314)		-0.760** (0.185)		-1.272** (0.325)	
Sub-humid (moist)	1.275* (0.563)		0.642 (0.483)		1.410* (0.625)	
Constant	7.649*** (1.389)		6.497*** (1.515)		8.457*** (1.418)	
Observations	4124		3288		3406	
Adjusted R^2	0.781		0.782		0.796	

Appendix 5d: OLS models explaining simulated frequency of years when net profit is negative - across climate scenarios (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	(1)		(2)		(3)	
	historic climate		wet cool scenario		hot dry scenario	
	coef.	rank	coef.	rank	coef.	rank
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	6.301*** (0.397)	11	7.475*** (0.370)	11	5.269*** (0.631)	11
Maize-Chickpea	1.416** (0.397)	7	0.595 (0.378)		1.219 (0.631)	
Sorghum-Fallow	-1.123* (0.386)	1	-1.264** (0.363)	1	-1.731* (0.641)	1
Sorghum-Wheat	0.244 (0.389)	6	0.0258 (0.377)		-0.110 (0.632)	
Millet-Sorghum	3.104*** (0.389)	9	2.118*** (0.375)	9	1.703* (0.632)	10
Mungbean-Sorghum	-0.492 (0.401)		-0.568 (0.381)		-0.958 (0.625)	
Pigeonpea-Fallow	-0.433 (0.390)		-0.894* (0.359)	2	-0.893 (0.632)	
Rice-Chickpea	-0.333 (0.397)		-0.0800 (0.376)		-0.761 (0.632)	
Soybean-Chickpea	2.083*** (0.395)	8	1.463** (0.375)	8	0.808 (0.632)	
Sorghum-Chickpea	0.0241 (0.397)		-0.357 (0.376)		-0.713 (0.631)	
Soybean-Maize	3.109*** (0.393)	10	2.589*** (0.372)	10	1.329 (0.631)	
Soil types (reference are Slightly deep inceptisols)						
Deep Entisol	-2.371*** (0.519)		-1.855*** (0.401)		-1.955*** (0.443)	
Deep Vertisol	-0.469* (0.195)		-0.426 (0.240)		-0.212 (0.139)	
Extremly shallow Entisols	11.91*** (2.105)		12.81*** (2.081)		12.72*** (2.103)	
Slightly deep Entisols	0.254 (0.209)		-0.396 (0.188)		0.0803 (0.179)	
Shallow inceptisols	0.0308 (0.146)		0.733** (0.206)		0.631** (0.188)	
Very Deep Inceptisols	0.0653 (0.176)		0.827** (0.212)		0.737** (0.196)	
Very Deep Vertisol	-0.108 (0.211)		0.156 (0.377)		0.272 (0.218)	
Very shallow Entisols	5.265* (1.858)		4.965* (1.733)		5.477** (1.724)	
Very shallow inceptisols	5.820** (1.821)		5.365** (1.710)		5.821** (1.414)	
Agro-ecological zones (reference is Sub-humid (dry)						
Semi-arid (dry)	2.832*** (0.591)		2.600*** (0.589)		2.428*** (0.549)	
Semi-arid (moist)	0.198 (0.0986)		0.176 (0.0883)		0.114 (0.0828)	
Sub-humid (moist)	-0.255 (0.199)		-0.199 (0.208)		-0.257 (0.176)	
Constant	-1.111 (0.628)		-1.115* (0.518)		-0.704 (0.713)	
Observations	4124		3288		3406	
Adjusted R^2	0.460		0.490		0.488	

Appendix 6a: Mixed effects models explaining simulated net profit in INR/ha across agro-ecological zones; (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	semi-arid (dry)		semi-arid (moist)		subhumid (dry)		subhumid (moist)	
	coef.	rank	coef.	rank	coef.	rank	coef.	rank
Management Parameters								
manure in kg	2.554*** (0.185)		2.476*** (0.0708)		3.605*** (0.197)		4.928*** (0.518)	
fertilizer in kg	122.1*** (6.992)		137.3*** (2.754)		197.3*** (7.851)		239.7*** (19.84)	
irrigation in mm	16.76*** (1.854)		-2.753** (0.972)		-22.34*** (2.737)		-16.92** (6.175)	
Climate variables								
Av. min. temperature in ^{o}C	2876.8*** (311.3)		1882.9*** (122.0)		1674.9*** (377.8)		5126.4*** (980.3)	
August rainfall in mm	30.94*** (1.710)		7.736*** (0.487)		1.927 (1.124)		0.972 (2.292)	
Number of annual rainy days	154.6*** (12.17)		217.1*** (5.161)		-46.16*** (13.16)		-145.9*** (32.86)	
Consecutive dry days during monsoon	-111.8*** (26.17)		146.5*** (11.73)		-339.6*** (34.14)		22.86 (72.70)	
solar radiation	3114.7*** (203.6)		4850.7*** (96.89)		4003.8*** (301.6)		-4466.9*** (706.0)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)								
Cotton-Fallow	10757.8* (4660.4)	8	27391*** (3656.2)	7	76705.9*** (12115.5)	6	129851*** (5021.6)	6
Maize-Chickpea	19282*** (4662)	6	41670*** (3656.8)	5	101462*** (12121.0)	3	151685*** (5136.7)	2
Sorghum-Fallow	24191*** (4661.7)	5	21078*** (3658.7)	9	30417.2* (12123.5)	11	42522*** (5173)	11
Sorghum-Wheat	27087*** (4669)	4	25174*** (3656.8)	8	45589.1*** (12118.3)	10	60932*** (5099)	10
Millet-Sorghum	8453.9 (4646.7)		17596*** (3652.7)	10	49888.6*** (12109.2)	9	74279*** (4960)	8
Mungbean- Sorghum	55016*** (4635.3)	1	65135*** (3650.6)	1	100338*** (12105.3)	4	131012*** (4907.4)	5
Pigeonpea-Fallow	46366*** (4669.0)	2	48753*** (3658.4)	3	61934.8*** (12120.2)	8	71497*** (5042.1)	9
Rice-Chickpea	13178.0** (4854.8)	7	45716*** (3707.9)	4	113378*** (12209.2)	2	150873*** (5807.7)	3
Soybean-Chickpea	8894.5 (4646.8)		35428*** (3653.8)	6	98374.5*** (12112.9)	5	146542*** (4989.6)	4
Sorghum- Chickpea	39896*** (4645.8)	3	59048*** (3653.7)	2	124082*** (12112.9)	1	180606*** (4989.6)	1
Soybean-Maize	-7752.4 (4671.5)		17309*** (3657.5)	11	67445.1*** (12119.8)	7	100427*** (5111.7)	7
Soil types (reference are Slightly deep inceptisols)								
Deep Entisol	28172.2*** (3601)							
Deep Vertisol	41970.8*** (3587)		38591.8*** (3524)					
Extremly shallow Entisols	-57598*** (4641)		-50372*** (5470)					
Slightly deep Entisols	-3261.0 (4643.3)		-6346.1 (3903.5)					
Shallow inceptisols	-11319.7** (3596)		-9529.5* (4665.9)		15682.3 (10506.9)		Very Deep Vertisol is the only soil type in this agro-ecological zone	
Very Deep Inceptisols			-3569.6 (4669.1)					
Very Deep Vertisol			58225.1*** (2870)		88318*** (8134.8)			
Very shallow Entisols	-41239*** (3178)		-37076*** (2832)					
Very shallow inceptisols			-44320*** (4667)					
Constant	-117471*** (6981)		-139887*** (3914)		-161353*** (12005)		-26315.8 (24501)	
Random-effects parameters								
Grid	-1.281 (25.80)		-2.797 (2.770)		-3.270 (9.277)		-4.076 (20.89)	

Cropping System	9.679*** (0.0478)	10.20*** (0.0221)	10.26*** (0.0724)	8.332*** (0.239)
Residual	10.03*** (0.003)	10.04*** (0.00149)	10.08*** (0.00413)	10.12*** (0.0102)
Observations	42489	225541	30007	4855

Appendix 6b: Mixed effects models explaining simulated total ecosystem service value in INR/ha across agro-ecological zones; (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	semi-arid (dry)		semi-arid (moist)		subhumid (dry)		subhumid (moist)	
	coef.	rank	coef.	rank	coef.	rank	coef.	rank
Management Parameters								
manure in kg	2.528*** (0.197)		2.514*** (0.0733)		3.774*** (0.202)		5.137*** (0.520)	
fertilizer in kg	86.13*** (7.466)		104.9*** (2.856)		169.5*** (8.039)		207.9*** (19.81)	
irrigation in mm	70.01*** (3.149)		28.32*** (1.417)		-9.670* (4.033)		-17.66** (6.213)	
Climate variables								
Av. min. temperature in °C	3352.1*** (326.9)		1451.6*** (126.9)		763.3* (387.1)		4995.1*** (985.5)	
August rainfall in mm	28.88*** (1.826)		4.445*** (0.517)		0.788 (1.138)		-0.0633 (2.295)	
Number of annual rainy days	247.9*** (12.81)		290.4*** (5.355)		-9.619 (13.39)		-151.7*** (32.70)	
Consecutive dry days during monsoon	-96.34*** (27.90)		211.1*** (12.23)		-177.9*** (35.55)		107.1 (72.56)	
solar radiation	1983.1*** (212.5)		3792.5*** (100.1)		2912.7*** (307.0)		-6157.5*** (713.9)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)								
Cotton-Fallow	10201.9 (6130.8)		20664*** (3944.6)	7	63336.1*** (12565.5)	7	111106*** (4453.2)	6
Maize-Chickpea	6021.9 (6123.0)		27286*** (3943.9)	5	89427.4*** (12571.4)	3	140500*** (4586.4)	2
Sorghum-Fallow	29301*** (6134.7)	3	20960*** (3947.8)	6	27082.2* (12575.2)	10	37714*** (4605.4)	10
Sorghum-Wheat	391.5 (6120.3)		-3864.9 (3941.7)		17695.2 (12561.3)		32161*** (4531.2)	11
Millet-Sorghum	-6078.7 (6101.2)		2279.9 (3937.7)		34287.4** (12552.1)	9	58551*** (4375.3)	9
Mungbean- Sorghum	41300*** (6091.2)	2	50655*** (3935.6)	2	85660.9*** (12548.3)	5	115833*** (4318.2)	5
Pigeonpea-Fallow	58638*** (6140.3)	1	56965*** (3947.5)	1	67206.1*** (12571.9)	6	74046*** (4466.0)	8
Rice-Chickpea	-51572*** (6521.6)	11	-246.9 (4039.6)	10	88053.1*** (12742.7)	4	136456*** (5258.7)	4
Soybean-Chickpea	950.5 (6111.7)		27491*** (3941.4)	4	92714.8*** (12563.9)	2	140042*** (4430.7)	3
Sorghum- Chickpea	26234*** (6108.6)	4	43982*** (3940.6)	3	111483*** (12562.6)	1	168181*** (4412.7)	1
Soybean-Maize	-22902*** (6122.7)	10	2709.9 (3942.4)		55600.8*** (12562.8)	8	89132*** (4545.9)	7
Soil types (reference are Slightly deep inceptisols)								
Deep Entisol	31734.3*** (4728)							
Deep Vertisol	43400.5*** (4716)		40365.6*** (3799)					
Extremly shallow Entisols	-61463*** (6096)		-50339*** (5897)					
Slightly deep Entisols	63.60 (6102.0)		-5852.7 (4208.1)				Very Deep Vertisol is the only soil type in this agro-	
Shallow inceptisols	-12298.3** (4724)		-8676.2 (5029.7)		17111.3 (10891.0)			
Very Deep Inceptisols			-1636.1 (5033.4)					
Very Deep Vertisol			62365.9*** (3094)		92006*** (8432.2)			

Very shallow Entisols	-42325*** (4171)	-37258*** (3053)		ecological zone
Very shallow inceptisols		-44909*** (5031)		
Constant	-133875*** (7680)	-132489*** (4181)	-139724*** (12480)	-2985.6 (24947.1)
Random-effects parameters				
Grid	-1.553 (61.17)	-2.523 (3.125)	-3.241 (8.602)	-3.190 (25.14)
Cropping System	9.954*** (0.0517)	10.28*** (0.0222)	10.30*** (0.0693)	8.187*** (0.234)
Residual	10.06*** (0.0036)	10.06*** (0.00152)	10.08*** (0.00418)	10.11*** (0.0103)
Observations	39958	217139	28760	4699

Appendix 6c: Mixed effects models explaining simulated total net profit per unit evapotranspiration in INR/m^3 across agro-ecological zones; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	semi-arid (dry)		semi-arid (moist)		subhumid (dry)		subhumid (moist)	
	coef.	rank	coef.	rank	coef.	rank	coef.	rank
Management Parameters								
manure in kg	0.0003*** (0.00003)		0.0003*** (0.00001)		0.0004*** (0.00002)		0.0005*** (0.0001)	
fertilizer in kg	0.0152*** (0.001)		0.016*** (0.0004)		0.0231*** (0.0009)		0.0258*** (0.0022)	
irrigation in mm	0.0028*** (0.0003)		-0.0003* (0.0001)		-0.0029*** (0.0003)		-0.0035*** (0.001)	
Climate variables								
Av. min. temperature in °C	0.394*** (0.0462)		0.188*** (0.0157)		0.141** (0.0452)		0.632*** (0.109)	
August rainfall in mm	0.005*** (0.0003)		0.0009*** (0.0001)		0.00035** (0.0001)		0.0014*** (0.0003)	
No. of annual rainy days	0.0337*** (0.00181)		0.035*** (0.0007)		0.00411** (0.0016)		-0.0186*** (0.004)	
Consecutive dry days during monsoon	-0.00193 (0.00389)		0.0187*** (0.002)		-0.0328*** (0.004)		0.00876 (0.0081)	
solar radiation	0.112*** (0.0303)		0.214*** (0.0125)		0.138*** (0.0361)		-0.810*** (0.0787)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)								
Cotton-Fallow	-3.103*** (0.581)	9	-1.320*** (0.381)	8	3.619** (1.290)	8	8.404*** (1.340)	7
Maize-Chickpea	-2.300*** (0.581)	5	-0.208 (0.381)		5.813*** (1.290)	5	10.42*** (1.346)	5
Sorghum-Fallow	2.892*** (0.581)	2	2.460*** (0.381)	3	4.298*** (1.291)	7	6.294*** (1.349)	8
Sorghum-Wheat	-2.775*** (0.582)	7	-3.243*** (0.381)	11	-1.931 (1.290)		-1.276 (1.343)	11
Millet-Sorghum	-2.662*** (0.578)	6	-1.513*** (0.380)	9	2.181 (1.289)		4.853*** (1.336)	10
Mungbean- Sorghum	2.626*** (0.576)	3	3.939*** (0.380)	2	8.015*** (1.288)	2	10.99*** (1.333)	4
Pigeonpea-Fallow	9.110*** (0.582)	1	9.865*** (0.381)	1	12.71*** (1.290)	1	13.86*** (1.343)	1
Rice-Chickpea	-4.838*** (0.613)	10	-0.957* (0.389)	7	5.552*** (1.302)	6	9.000*** (1.411)	6
Soybean-Chickpea	-2.857*** (0.578)	8	-0.214 (0.380)		6.723*** (1.289)	4	11.19*** (1.340)	3
Sorghum- Chickpea	-0.234 (0.578)		1.269*** (0.380)	4	7.446*** (1.289)	3	12.15*** (1.340)	2
Soybean-Maize	-5.111*** (0.583)	11	-2.632*** (0.381)	10	2.333 (1.290)		5.273*** (1.343)	9

Soil types (reference are Slightly deep inceptisols)				
Deep Entisol	3.026*** (0.448)			
Deep Vertisol	4.838*** (0.446)	4.437*** (0.367)		
Extremly shallow Entisols	-8.244*** (0.577)	-6.810*** (0.569)		
Slightly deep Entisols	-0.242 (0.578)	-0.957* (0.406)		Very Deep Vertisol is the only soil type in this agro-ecological zone
Shallow inceptisols	-1.401** (0.447)	-1.259** (0.486)	2.070 (1.119)	
Very Deep Inceptisols		-0.734 (0.486)		
Very Deep Vertisol		6.356*** (0.299)	10.32*** (0.867)	
Very shallow Entisols	-6.078*** (0.396)	-5.153*** (0.295)		
Very shallow inceptisols		-6.187*** (0.486)		
Constant	-7.170*** (1.013)	-5.022*** (0.460)	-7.602*** (1.355)	6.338* (2.786)
Random-effects parameters				
Grid	-11.31 (117.6)	-12.57*** (2.631)	-11.45 (7.649)	-10.80 (21.62)
Cropping System	0.684*** (0.0485)	1.033*** (0.0222)	1.113*** (0.0694)	0.167 (0.189)
Residual	1.214*** (0.00344)	1.087*** (0.00149)	1.048*** (0.00409)	1.019*** (0.0102)
Observations	42489	225541	30007	4855

Appendix 7a: OLS models explaining simulated net profit in INR/ha across agro-ecological zones (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) semi-arid (dry) coef.	rank	(2) semi-arid (moist) coef.	rank	(3) subhumid (dry) coef.	rank	(4) subhumid (moist) coef.	rank
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)								
Cotton-Fallow	22842.5**	7	47004.0***	5	130836.2***	5	133526.6***	5
	(6810.3)		(6315.2)		(6411.2)		(2004.5)	
Maize-Chickpea	29802.4***	6	61746.0***	4	155793.0***	2	161407.6***	2
	(6852.0)		(6331.3)		(6411.4)		(2004.5)	
Sorghum-Fallow	19267.8*	8	19116.8**	11	42135.4***	11		
	(6782.0)		(6100.2)		(6408.3)			
Sorghum-Wheat	36721.6***	4	36665.1***	9	80224.8***	9	73320.3***	9
	(6806.3)		(6306.9)		(6408.1)		(2106.4)	
Millet-Sorghum	16187.4*	9	27985.9***	10	80231.2***	8	78174.6***	8
	(6780.2)		(6302.6)		(6410.3)		(2106.4)	
Mungbean- Sorghum	60956.4***	1	74041.1***	2	127509.6***	6	126377.9***	6
	(6846.5)		(6256.4)		(6411.1)		(2004.5)	
Pigeonpea-Fallow	34318.2***	5	40843.0***	7	59943.1***	10	57013.2***	10
	(6769.6)		(6203.3)		(6413.5)		(2004.5)	
Rice-Chickpea	38630.5***	3	64751.2***	3	151440.7***	3	149453.6***	3
	(6831.1)		(6337.6)		(6411.4)		(2004.5)	
Soybean-Chickpea	10357.0		46426.3***	6	138376.9***	4	141062.7***	4
	(6797.8)		(6321.4)		(6411.4)		(2004.5)	
Sorghum- Chickpea	45013.7***	2	74111.6***	1	173822.1***	1	174727.5***	1
	(6840.6)		(6324.8)		(6411.4)		(2004.5)	
Soybean-Maize	3923.0		37324.5***	8	113106.4***	7	111441.7***	7
	(6767.6)		(6308.4)		(6411.4)		(2004.5)	
Climate scenarios (reference are observed climate data over the past 30 years)								
Future-Cool wet	2129.0 (1846.0)		-401.4 (1514.8)		-7157.5*** (1519.5)		-8019.8*** (1642)	
Future-Hot dry	10353.1** (2954.1)		8920.1** (2700.0)		12941.3** (3594.1)		17508.7* (5657.7)	
Soil types (reference are Slightly deep inceptisols)								
Deep Entisol	27621.0*** (6007)							
Deep Vertisol	42448.5*** (7163)		44134.6*** (7019)					
Extremly shallow Entisols	-53596.6*** (4610)		-42527.5*** (3936)					
Slightly deep Entisols	-7678.6* (2586.7)		-7258.5*** (1576)					
Shallow inceptisols	-1084.0 (2664.9)		-1722.8 (2244.2)		-68509.0*** (6139.5)		Very Deep Vertisol is the only soil type in this agro-ecological zone	
Very Deep Inceptisols			7679.0 (3688.1)					
Very Deep Vertisol			68572.0*** (13717)		-5601.6 (5668.2)			
Very shallow Entisols	-43525.0*** (4501)		-33333.9*** (3626)					
Very shallow inceptisols			-37113.7*** (3857)					
Constant	26205.2** (7493.2)		13515.2 (8404.5)		37610.9*** (6116.7)		36693.7*** (1642)	
Observations	1644		8273		772		129	
Adjusted R^2	0.810		0.752		0.940		0.883	

Appendix 7b: OLS models explaining simulated total ecosystem service value in INR/ha across agro-ecological zones (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) semi-arid (dry)		(2) semi-arid (moist)		(3) subhumid (dry)		(4) subhumid (moist)	
	coef.	rank	coef.	rank	coef.	rank	coef.	rank
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)								
Cotton-Fallow	10452.2 (5115.2)		32649.1*** (5187.5)	7	112049.2*** (5228.3)	6	118447.0*** (2137.6)	5
Maize-Chickpea	8203.8 (5171.4)		42545.3*** (5208.1)	4	142717.1*** (5228.1)	2	153156.8*** (2137.6)	2
Sorghum-Fallow	14416.5* (5081.7)	4	14078.4* (4913.8)	9	37760.2*** (5225.7)	11		
Sorghum-Wheat	6683.6 (5112.1)		5606.7 (5175.4)		51263.8*** (5225.5)	10	46693.3*** (2230.5)	10
Millet-Sorghum	-117.2 (5080.1)		11671.2* (5171.5)	10	63727.8*** (5226.9)	8	65845.1*** (2230.5)	8
Mungbean- Sorghum	46023.6*** (5168.9)	1	59430.1*** (5109.2)	1	112855.2*** (5228.7)	5	115390.1*** (2137.6)	6
Pigeonpea-Fallow	37032.1*** (5064.5)	2	44510.8*** (5046.6)	3	63593.0*** (5236.1)	9	65647.6*** (2137.6)	9
Rice-Chickpea	10391.6 (5140.8)		39531.5*** (5215.5)	5	135672.0*** (5228.1)	3	137808.9*** (2137.6)	4
Soybean-Chickpea	-3337.1 (5091.3)		36126.0*** (5181.6)	6	133753.8*** (5238.5)	4	141119.4*** (1856.0)	3
Sorghum- Chickpea	25927.3*** (5154.9)	3	56355.8*** (5199.1)	2	162039.7*** (5228.1)	1	167263.3*** (2137.6)	1
Soybean-Maize	-14715.4* (5061.2)	11	21182.5** (5180.9)	8	99816.7*** (5228.1)	7	102305.0*** (2137.6)	7
Climate scenarios (reference are observed climate data over the past 30 years)								
Future-Cool wet	2105.7 (1995.7)		-930.6 (1660.2)		-7894.0*** (1634.0)		-8817.2** (1928.5)	
Future-Hot dry	9807.9** (3120.5)		8298.6* (2827.0)		12833.0** (3647.1)		17468.6* (5796.5)	
Soil types (reference are Slightly deep inceptisols)								
Deep Entisol	27732.4*** (6157)							
Deep Vertisol	42401.9*** (7335)		44889.0*** (7345)					
Extremly shallow Entisols	-57524.4*** (4999)		-44914.8*** (4416)					
Slightly deep Entisols	-8212.2* (2873.2)		-9135.3*** (2141)					
Shallow inceptisols	-1079.6 (2930.3)		-1173.9 (2504.9)		-71213.2*** (5764.6)		Very Deep Vertisol is the only soil type in this agro-ecological zone	
Very Deep Inceptisols			8107.1* (3730.8)					
Very Deep Vertisol			69911.9*** (14284)		-8020.8 (4959.8)			
Very shallow Entisols	-46617.5*** (4734)		-34947.9*** (3866)					
Very shallow inceptisols			-39066.9*** (4222)					
Constant	13582.9* (5985.2)		527.6 (7588.2)		27069.6*** (1620.2)		19115.3*** (1929)	
Observations	1635		8226		767		128	
Adjusted R^2	0.804		0.723		0.932		0.884	

Appendix 7c: OLS models explaining simulated net profit per unit evapotranspiration in INR/m^3 across agro-ecological zones (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	(1) semi-arid (dry) coef.	rank	(2) semi-arid (moist) coef.	rank	(3) subhumid (dry) coef.	rank	(4) subhumid (moist) coef.	rank
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)								
Cotton-Fallow	-2.486		0.673		9.352***	6	11.09***	6
	(1.236)		(1.160)		(1.184)		(0.208)	
Maize-Chickpea	-1.471		1.706		11.49***	3	13.80***	3
	(1.242)		(1.162)		(1.185)		(0.208)	
Sorghum-Fallow	2.380		2.234		7.016***	9		
	(1.234)		(1.137)		(1.184)			
Sorghum-Wheat	-1.825		-2.399		1.145	11	1.999***	10
	(1.237)		(1.160)		(1.184)		(0.214)	
Millet-Sorghum	-1.901		-0.343		5.664***	10	7.329***	9
	(1.233)		(1.159)		(1.185)		(0.214)	
Mungbean- Sorghum	3.058*	2	4.837***	2	11.10***	4	12.48***	5
	(1.244)		(1.160)		(1.184)		(0.208)	
Pigeonpea-Fallow	7.300***	1	9.140***	1	13.02***	1	14.63***	1
	(1.231)		(1.150)		(1.182)		(0.208)	
Rice-Chickpea	-1.688		0.613		8.665***	7	10.08***	7
	(1.238)		(1.163)		(1.185)		(0.208)	
Soybean-Chickpea	-2.986*	10	0.796		11.08***	5	12.93***	4
	(1.235)		(1.160)		(1.185)		(0.208)	
Sorghum- Chickpea	-0.0789		2.383		12.20***	2	13.85***	2
	(1.240)		(1.162)		(1.185)		(0.208)	
Soybean-Maize	-3.872**	11	-0.627		7.045***	8	8.453***	8
	(1.230)		(1.158)		(1.185)		(0.208)	
Climate scenarios (reference are observed climate data over the past 30 years)								
Future-Cool wet	0.207 (0.256)		-0.206 (0.220)		-0.930*** (0.205)		-1.043** (0.236)	
Future-Hot dry	1.144* (0.444)		0.754 (0.412)		1.145* (0.433)		1.437* (0.573)	
Soil types (reference are Slightly deep inceptisols)								
Deep Entisol	2.674*** (0.598)							
Deep Vertisol	4.814*** (0.602)		4.828*** (0.679)					
Extremly shallow Entisols	-7.840*** (0.798)		-6.008*** (0.495)					
Slightly deep Entisols	-1.063** (0.295)		-1.319*** (0.278)					
Shallow inceptisols	-0.326 (0.377)		-0.272 (0.315)		-8.687*** (0.972)		Very Deep Vertisol is the only soil type in this agro-ecological zone	
Very Deep Inceptisols			0.669 (0.511)					
Very Deep Vertisol			7.503*** (1.385)		-0.720 (0.924)			
Very shallow Entisols	-6.530*** (0.789)		-4.660*** (0.449)					
Very shallow inceptisols			-5.237*** (0.492)					
Constant	7.430*** (1.335)		6.211*** (1.386)		9.184*** (0.704)		6.927*** (0.236)	
Observations	1644		8273		772		129	
Adjusted R^2	0.826		0.775		0.863		0.865	

Appendix 7d: OLS models explaining simulated frequency of the net profit being negative over 30 years across agro-ecological zones (including climate scenarios); (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	(1)		(2)		(3)		(4)	
	semi-arid (dry)		semi-arid (moist)		subhumid (dry)		subhumid (moist)	
	coef.	rank	coef.	rank	coef.	rank	coef.	rank
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)								
Cotton-Fallow	4.445** (1.110)	11	7.337*** (0.361)	11	0.193* (0.0832)		0.258*** (0.0282)	
Maize-Chickpea	2.094 (1.089)		0.937* (0.362)	7	-0.136 (0.0830)		0.0270 (0.0282)	
Sorghum-Fallow	-3.555** (1.115)	1	-0.943* (0.344)	1	-0.137 (0.0835)			
Sorghum-Wheat	-1.233 (1.104)		0.211 (0.361)		-0.137 (0.0836)		0.0267 (0.0279)	
Millet-Sorghum	2.395* (1.115)	8	2.561*** (0.359)	10	-0.137 (0.0831)		0.0267 (0.0279)	
Mungbean- Sorghum	-2.350* (1.071)	3	-0.504 (0.376)		-0.136 (0.0835)		0.0270 (0.0282)	
Pigeonpea-Fallow	-2.470* (1.125)	2	-0.559 (0.352)		-0.133 (0.0850)		0.0270 (0.0282)	
Rice-Chickpea	-1.635 (1.101)		-0.331 (0.363)		-0.136 (0.0830)		0.0270 (0.0282)	
Soybean-Chickpea	3.424** (1.111)	9	1.228** (0.359)	8	-0.136 (0.0830)		0.0270 (0.0282)	
Sorghum- Chickpea	-1.567 (1.095)		-0.245 (0.362)		-0.136 (0.0830)		0.0270 (0.0282)	
Soybean-Maize	4.171** (1.128)	10	2.287*** (0.357)	9	-0.136 (0.0830)		0.0270 (0.0282)	
Climate scenarios (reference are observed climate data over the past 30 years)								
Future-Cool wet	-0.341 (0.165)		-0.156 (0.164)		0.0561 (0.0609)		0.0301 (0.0315)	
Future-Hot dry	-0.329 (0.201)		-0.0350 (0.171)		0.0433 (0.0489)		-0.0199 (0.0208)	
Soil types (reference are Slightly deep inceptisols)								
Deep Entisol	-0.169 (0.197)							
Deep Vertisol	-0.391* (0.149)		-0.319 (0.212)					
Extremly shallow Entisols	17.70*** (2.541)		8.416** (2.102)					
Slightly deep Entisols	1.314** (0.368)		-0.162 (0.0895)					
Shallow inceptisols	2.558*** (0.557)		-0.182 (0.159)		-0.370 (0.416)		Very Deep Vertisol is the only soil type in this agro-ecological zone	
Very Deep Inceptisols			-0.147 (0.153)					
Very Deep Vertisol			-0.545* (0.229)		-0.367 (0.422)			
Very shallow Entisols	11.82*** (2.701)		4.081* (1.718)					
Very shallow inceptisols			5.045** (1.595)					
Constant	0.454 (0.981)		-0.241 (0.546)		0.472 (0.391)		-0.0301 (0.0315)	
Observations	1644		8273		772		129	
Adjusted R^2	0.686		0.421		0.151		0.047	

Appendix 8a: Mixed effects models explaining simulated outcome variables for Deep Vertisol soils; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha		Total ESS value in INR/ha		Net profit by evapo-transpiration in INR/m^3	
	coef.	rank	coef.	rank	coef.	rank
Year of cultivation	-357.9*** (78.07)		-139.1 (85.76)		0.00270 (0.0123)	
Management Parameters						
manure in kg	2.841*** (0.598)		2.991*** (0.630)		0.000240* (0.0000943)	
fertilizer in kg	191.5*** (22.22)		156.9*** (23.47)		0.0229*** (0.00353)	
irrigation in mm	39.98*** (8.310)		43.07*** (9.105)		0.0123*** (0.00156)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	61705.8*** (8260.5)	5	50772.7*** (9651.7)	4	2.511 (2.397)	
Maize-Chickpea	61840.3*** (8228.0)	4	45093.0*** (9616.8)	6	1.615 (2.393)	
Sorghum-Fallow	27743.5*** (8296.6)	10	22689.8* (9689.6)	7	4.682 (2.402)	
Sorghum-Wheat	39883.4*** (8322.0)	7	13480.4 (9706.0)		-2.990 (2.400)	
Millet-Sorghum	38044.5*** (8206.9)	9	21463.5* (9596.0)	8	-0.202 (2.390)	
Mungbean- Sorghum	81689.2*** (8109.2)	2	66346.0*** (9503.9)	3	4.435 (2.382)	
Pigeonpea-Fallow	64248.6*** (8326.5)	3	67337.9*** (9717.6)	2	13.73*** (2.404)	1
Rice-Chickpea	38847.0*** (9279.5)	8	8545.3 (10714.0)		-8.199** (2.528)	11
Soybean-Chickpea	58991.4*** (8171.4)	6	48608.1*** (9580.8)	5	2.406 (2.388)	
Sorghum- Chickpea	85492.6*** (8130.4)	1	70641.2*** (9523.7)	1	4.581 (2.384)	
Soybean-Maize	-1005.6 (8351.5)		-15202.4 (9734.7)		-5.657* (2.403)	
Climate variables						
Average minimum temperature in ^{o}C	-2619.6** (875.6)		-1285.7 (913.9)		-0.376** (0.138)	
August rainfall in mm	110.7*** (8.026)		104.0*** (8.356)		0.0127*** (0.00126)	
Number of annual rainy days	324.7*** (35.54)		411.0*** (37.16)		0.0580*** (0.00561)	
Consecutive dry days during monsoon	-188.1 (134.0)		22.25 (142.1)		-0.0156 (0.0211)	
solar radiation	10120.0*** (724.9)		7187.1*** (796.7)		0.628*** (0.114)	
Constant	564132.5*** (145145.3)		137249.0 (159895.8)		-8.767 (22.87)	
Random-effects parameters						
Cropping system	8.874*** (0.257)		9.035*** (0.273)		0.752*** (0.216)	
Residual	10.22*** (0.00896)		10.26*** (0.00916)		1.468*** (0.00896)	
Observations	6255		5996		6255	

Appendix 8b: Mixed effects models explaining simulated outcome variables for Deep Entisol soils; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha		Total ESS value in INR/ha		Net profit by evapo-transpiration in INR/m³	
	coef.	rank	coef.	rank	coef.	rank
Year of cultivation	-236.5*** (28.85)		-152.5*** (29.65)		0.000870 (0.00391)	
Management Parameters						
manure in kg	2.827*** (0.251)		2.942*** (0.257)		0.000240*** (0.000034)	
fertilizer in kg	148.0*** (9.329)		118.0*** (9.576)		0.0172*** (0.00126)	
irrigation in mm	80.88*** (4.383)		81.87*** (4.508)		0.0103*** (0.000597)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	82051.1*** (18794)	3	66492.1** (20332)	4	3.679 (3.115)	
Maize-Chickpea	79157.9*** (18789)	4	62308.8** (20326)	5	2.027 (3.115)	
Sorghum-Fallow	54987.3** (18803)	7	50336.2* (20339.9)	7	7.628* (3.116)	2
Sorghum-Wheat	53184.1** (18786)	9	26162.0 (20323.3)		-2.648 (3.114)	
Millet-Sorghum	54159.1** (18777)	8	38863.7 (20314.8)		1.323 (3.113)	
Mungbean- Sorghum	105425*** (18774)	2	91840.7*** (20311)	2	6.983* (3.113)	3
Pigeonpea-Fallow	76346.7*** (18802)	5	78782.3*** (20339)	3	13.94*** (3.116)	1
Rice-Chickpea	23256.5 (19031.4)		3623.5 (20563.1)		-6.663* (3.142)	11
Soybean-Chickpea	69530.8*** (18783)	6	59412.9** (20322)	6	2.032 (3.114)	
Sorghum- Chickpea	112853*** (18782)	1	97108.5*** (20319)	1	5.133 (3.114)	
Soybean-Maize	37939.2* (18789.9)	10	24990.4 (20327.0)		-2.207 (3.115)	
Climate variables						
Average minimum temperature in °C	-346.3* (158.0)		-488.5** (162.5)		-0.109*** (0.0214)	
August rainfall in mm	31.45*** (1.702)		31.15*** (1.749)		0.00355*** (0.000231)	
Number of annual rainy days	671.8*** (17.66)		729.4*** (18.16)		0.0837*** (0.00239)	
Consecutive dry days during monsoon	238.4*** (37.28)		297.0*** (38.32)		0.0411*** (0.00505)	
solar radiation	8612.8*** (320.6)		7317.1*** (329.5)		0.344*** (0.0434)	
Constant	285147.4*** (54912.6)		130273.6* (56512.9)		-4.529 (7.485)	
Random-effects parameters						
Cropping system	9.728*** (0.188)		9.807*** (0.188)		1.024*** (0.186)	
Residual	10.28*** (0.00389)		10.30*** (0.00390)		1.373*** (0.00389)	
Observations	33040		32836		33040	

Appendix 8c: Mixed effects models explaining simulated outcome variables for Extremly shallow Entisols soils; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha		Total ESS value in INR/ha		Net profit by evapo-transpiration in INR/m^3	
	coef.	rank	coef.	rank	coef.	rank
Year of cultivation	41.84 (27.94)		-9.092 (31.82)		0.0186*** (0.00538)	
Management Parameters						
manure in kg	-0.141 (0.195)		-0.376 (0.222)		-0.0000452 (0.000038)	
fertilizer in kg	53.31*** (7.598)		13.23 (8.583)		0.00807*** (0.00150)	
irrigation in mm	12.92*** (1.810)		5.961** (1.957)		0.00411*** (0.000421)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	-20077.1*** (2050)	11	-27576.7*** (2091)	6	-4.121*** (0.76)	10
Maize-Chickpea	-7122.9*** (2065.8)	5	-29488.1*** (2112)	7	-1.738* (0.754)	6
Sorghum-Fallow	6766.4*** (2046.1)	3	-1732.6 (2084.2)		0.944 (0.753)	
Sorghum-Wheat	-10487.9*** (2077)	7	-42045.3*** (2127)	10	-2.512*** (0.76)	7
Millet-Sorghum	-18639.8*** (2027)	10	-32490.1*** (2064)	8	-3.350*** (0.75)	9
Mungbean- Sorghum	13944.6*** (2010.3)	2	427.1 (2043.0)		0.583 (0.748)	
Pigeonpea-Fallow	25839.1*** (2061.4)	1	25679.7*** (2103.0)	1	5.540*** (0.755)	1
Rice-Chickpea	-18565.6*** (2424)	9	-45834.6*** (2511)	11	-5.273*** (0.81)	11
Soybean-Chickpea	-8871.9*** (2019.5)	6	-24246.5*** (2061)	4	-1.724* (0.750)	5
Sorghum- Chickpea	-2470.9 (2019.1)		-26712.3*** (2053)	5	-1.157 (0.750)	
Soybean-Maize	-18517.3*** (2089)	8	-36267.0*** (2141)	9	-3.222*** (0.76)	8
Climate variables						
Average minimum temperature in °C	3487.8*** (205.8)		4148.2*** (234.2)		0.496*** (0.0397)	
August rainfall in mm	32.14*** (1.352)		34.50*** (1.540)		0.00597*** (0.000261)	
Number of annual rainy days	169.6*** (14.38)		200.2*** (16.37)		0.0355*** (0.00277)	
Consecutive dry days during monsoon	207.6*** (31.72)		224.3*** (36.13)		0.0319*** (0.00611)	
solar radiation	2737.9*** (388.7)		2106.3*** (442.6)		0.372*** (0.0749)	
Constant	-235806.9*** (51862.2)		-149140.3* (59052.8)		-59.09*** (9.997)	
Random-effects parameters						
Cropping system	7.451*** (0.229)		7.456*** (0.241)		-0.413* (0.210)	
Residual	9.276*** (0.00877)		9.403*** (0.00879)		0.721*** (0.00877)	
Observations	6526		6493		6526	

Appendix 8d: Mixed effects models explaining simulated outcome variables for Slightly deep Entisols soils; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha		Total ESS value in INR/ha		Net profit by evapo-transpiration in INR/m³	
	coef.	rank	coef.	rank	coef.	rank
Year of cultivation	-396.4*** (36.36)		-337.0*** (39.87)		-0.0356*** (0.00639)	
Management Parameters						
manure in kg	0.260 (0.292)		0.0922 (0.309)		-0.0000554 (0.000051)	
fertilizer in kg	157.2*** (10.72)		135.8*** (11.35)		0.0208*** (0.00189)	
irrigation in mm	35.90*** (5.198)		37.71*** (5.610)		0.00831*** (0.000968)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	6785.2 (7043.8)		-4212.7 (8317.6)		-3.222 (1.899)	
Maize-Chickpea	8725.7 (7034.8)		-11704.3 (8308.3)		-4.044* (1.897)	6
Sorghum-Fallow	27533.9*** (7047.2)	4	22320.3** (8321.3)	3	3.698 (1.899)	
Sorghum-Wheat	26483.0*** (7053.6)	5	-2767.1 (8325.9)		-4.308* (1.900)	7
Millet-Sorghum	-13118.4 (7014.6)		-29971.3*** (8289)	9	-6.151** (1.895)	9
Mungbean- Sorghum	38720.5*** (6995.5)	2	23711.5** (8270.5)	2	-0.372 (1.893)	
Pigeonpea-Fallow	53863.8*** (7062.0)	1	57517.3*** (8335.4)	1	10.87*** (1.901)	1
Rice-Chickpea	-18885.5* (7574.2)	10	-58494.0*** (8845)	11	-11.05*** (1.97)	11
Soybean-Chickpea	-2393.6 (7010.2)		-16853.5* (8288.3)	8	-4.708* (1.895)	8
Sorghum- Chickpea	31289.8*** (7009.9)	3	10660.9 (8284.6)		-1.666 (1.895)	
Soybean-Maize	-23225.3*** (7050)	11	-40755.4*** (8323)	10	-7.947*** (1.90)	10
Climate variables						
Average minimum temperature in °C	-1359.6*** (163.6)		-1997.0*** (172.0)		-0.313*** (0.0287)	
August rainfall in mm	5.558* (2.627)		6.485* (2.783)		0.000607 (0.000461)	
Number of annual rainy days	445.8*** (20.72)		492.2*** (21.81)		0.0736*** (0.00364)	
Consecutive dry days during monsoon	420.9*** (46.69)		477.3*** (49.12)		0.0641*** (0.00820)	
solar radiation	8646.3*** (425.9)		7506.8*** (462.6)		0.790*** (0.0748)	
Constant	649437.8*** (67698.3)		552605.4*** (74014.4)		64.62*** (11.91)	
Random-effects parameters						
Cropping system	8.736*** (0.204)		8.904*** (0.209)		0.524** (0.195)	
Residual	9.827*** (0.00683)		9.873*** (0.00691)		1.180*** (0.00683)	
Observations	10734		10490		10734	

Appendix 8e: Mixed effects models explaining simulated outcome variables for Slightly deep inceptisols soils; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha		Total ESS value in INR/ha		Net profit by evapo-transpiration in INR/m³	
	coef.	rank	coef.	rank	coef.	rank
Year of cultivation	-598.6*** (20.86)		-562.8*** (21.67)		-0.0609*** (0.00326)	
Management Parameters						
manure in kg	1.674*** (0.180)		1.845*** (0.187)		0.000190*** (0.000028)	
fertilizer in kg	128.8*** (6.963)		100.3*** (7.227)		0.0165*** (0.00109)	
irrigation in mm	44.99*** (3.221)		48.73*** (3.361)		0.00697*** (0.000508)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	4911.6 (13320.4)		-6556.9 (15484.9)		-3.656 (2.656)	
Maize-Chickpea	21360.7 (13315.1)		1893.7 (15479.9)		-3.131 (2.655)	
Sorghum-Fallow	28573.2* (13323.0)	5	24012.0 (15487.3)		2.952 (2.656)	
Sorghum-Wheat	33314.7* (13309.7)	3	6259.1 (15474.8)		-3.495 (2.654)	
Millet-Sorghum	3839.6 (13302.1)		-11560.3 (15467.7)		-4.155 (2.654)	
Mungbean- Sorghum	58166.5*** (13296)	2	44731.7** (15462)	2	1.999 (2.653)	
Pigeonpea-Fallow	62713.3*** (13324)	1	66449.5*** (15489)	1	12.04*** (2.656)	1
Rice-Chickpea	-26840.4* (13561)	11	-53298*** (15711)	11	-10.90*** (2.69)	11
Soybean-Chickpea	7144.8 (13309.6)		-6309.0 (15475.6)		-4.086 (2.654)	
Sorghum- Chickpea	33261.3* (13309.6)	4	13395.1 (15474.7)		-1.887 (2.655)	
Soybean-Maize	-4133.2 (13310.9)		-18184.0 (15475.9)		-5.921* (2.655)	10
Climate variables						
Average minimum temperature in °C	3728.9*** (147.4)		3406.6*** (153.1)		0.373*** (0.0230)	
August rainfall in mm	19.83*** (1.743)		21.93*** (1.810)		0.00290*** (0.000272)	
Number of annual rainy days	44.92*** (13.20)		60.77*** (13.71)		0.0127*** (0.00206)	
Consecutive dry days during monsoon	-204.7*** (26.77)		-215.4*** (27.80)		-0.0303*** (0.00418)	
solar radiation	7011.4*** (222.0)		6066.8*** (230.6)		0.562*** (0.0347)	
Constant	988331.8*** (40272.9)		928556.9*** (41954.8)		107.6*** (6.333)	
Random-effects parameters						
Cropping system	9.383*** (0.190)		9.534*** (0.190)		0.864*** (0.187)	
Residual	9.864*** (0.00424)		9.900*** (0.00425)		1.100*** (0.00424)	
Observations	27876		27738		27876	

Appendix 8f: Mixed effects models explaining simulated outcome variables for Shallow inceptisols soils; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha		Total ESS value in INR/ha		Net profit by evapo-transpiration in INR/m^3	
	coef.	rank	coef.	rank	coef.	rank
Year of cultivation	-154.4*** (28.39)		-177.2*** (30.51)		-0.0152*** (0.00462)	
Management Parameters						
manure in kg	1.283*** (0.252)		1.351*** (0.266)		0.000108** (0.0000410)	
fertilizer in kg	141.7*** (9.777)		113.1*** (10.35)		0.0179*** (0.00159)	
irrigation in mm	36.21*** (4.080)		39.36*** (4.402)		0.00620*** (0.000690)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	-10905.5 (8931.4)		-21147.0 (10886.2)		-5.149** (1.951)	9
Maize-Chickpea	15618.5 (8922.4)		-4225.0 (10877.3)		-2.853 (1.950)	
Sorghum-Fallow	22681.8* (8936.5)	4	17414.3 (10891.3)		2.233 (1.952)	
Sorghum-Wheat	9337.8 (8912.6)		-20711.1 (10867.5)		-4.788* (1.949)	8
Millet-Sorghum	6404.3 (8891.4)		-9382.8 (10848.1)		-3.110 (1.946)	
Mungbean- Sorghum	52987.9*** (8877.6)	2	39033.5*** (10835)	2	2.300 (1.944)	
Pigeonpea-Fallow	58418.1*** (8943.4)	1	62492.8*** (10898)	1	11.70*** (1.953)	1
Rice-Chickpea	-17732.8 (9449.8)		-44479*** (11384)	11	-9.240*** (2.02)	11
Soybean-Chickpea	5007.9 (8905.3)		-7500.8 (10863.9)		-3.511 (1.948)	
Sorghum- Chickpea	26093.4** (8905.3)	3	5039.4 (10861.6)		-1.805 (1.948)	
Soybean-Maize	-6784.5 (8915.6)		-20572.8 (10870.4)		-5.406** (1.949)	10
Climate variables						
Average minimum temperature in °C	1589.9*** (179.5)		1486.9*** (190.0)		0.116*** (0.0292)	
August rainfall in mm	0.160 (1.981)		1.737 (2.084)		0.000264 (0.000322)	
Number of annual rainy days	19.78 (17.07)		53.07** (17.97)		0.0114*** (0.00278)	
Consecutive dry days during monsoon	-294.6*** (32.06)		-310.4*** (33.80)		-0.0435*** (0.00521)	
solar radiation	3828.9*** (368.4)		3090.6*** (389.6)		0.300*** (0.0599)	
Constant	209482.7*** (53666.9)		257783.6*** (57608)		26.54** (8.745)	
Random-effects parameters						
Cropping system	8.977*** (0.212)		9.177*** (0.209)		0.552** (0.198)	
Residual	9.761*** (0.00673)		9.809*** (0.00681)		1.037*** (0.00673)	
Observations	11043		10793		11043	

Appendix 8g: Mixed effects models explaining simulated outcome variables for Very Deep Inceptisols soils; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha		Total ESS value in INR/ha		Net profit by evapo-transpiration in INR/m^3	
	coef.	rank	coef.	rank	coef.	rank
Year of cultivation	-653.6*** (45.94)		-653.2*** (46.97)		-0.0666*** (0.00618)	
Management Parameters						
manure in kg	0.279 (0.361)		0.361 (0.369)		-0.00002 (0.000049)	
fertilizer in kg	256.9*** (13.95)		226.1*** (14.30)		0.0296*** (0.00190)	
irrigation in mm	-1.958 (4.647)		-7.716 (5.107)		-0.000468 (0.000883)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	36593.8*** (4338.8)	4	19859.9*** (4958.1)	3	0.0366 (1.155)	
Maize-Chickpea	18427.3*** (4354.1)	7	-845.1 (4966.4)		-2.908* (1.153)	8
Sorghum-Fallow	17356.4*** (4338.9)	8	10207.2* (4961.7)	5	1.059 (1.157)	
Sorghum-Wheat	20517.1*** (4359.0)	5	-8902.4 (4967.0)		-4.259*** (1.15)	10
Millet-Sorghum	16621.1*** (4271.8)	9	1135.3 (4886.7)		-1.821 (1.146)	
Mungbean- Sorghum	66245.3*** (4193.1)	2	51614.6*** (4815.0)	2	3.586** (1.141)	2
Pigeonpea-Fallow	67949.4*** (4343.2)	1	70921.7*** (4966.1)	1	13.52*** (1.157)	1
Rice-Chickpea	14004.9** (5270.4)	10	-6429.7 (5953.7)		-3.939** (1.290)	9
Soybean-Chickpea	18648.7*** (4276.1)	6	4989.4 (4906.1)		-2.480* (1.148)	7
Sorghum- Chickpea	39284.4*** (4271.0)	3	18766.5*** (4890.6)	4	-0.952 (1.148)	
Soybean-Maize	-4035.6 (4370.4)		-18154.3*** (4978)	11	-5.339*** (1.15)	11
Climate variables						
Average minimum temperature in ^{o}C	5407.4*** (599.7)		5168.2*** (613.4)		0.419*** (0.0806)	
August rainfall in mm	-17.50*** (1.815)		-16.87*** (1.856)		-0.00166*** (0.00024)	
Number of annual rainy days	278.0*** (29.68)		334.4*** (30.38)		0.0481*** (0.00400)	
Consecutive dry days during monsoon	172.6** (63.89)		258.2*** (65.35)		0.0220* (0.00859)	
solar radiation	8460.5*** (551.0)		7874.4*** (563.4)		0.860*** (0.0741)	
Constant	1012991.5*** (86497.7)		1015264.3*** (88446.6)		109.7*** (11.64)	
Random-effects parameters						
Cropping system	8.203*** (0.211)		8.347*** (0.216)		0.0135 (0.198)	
Residual	9.962*** (0.00852)		9.982*** (0.00854)		1.047*** (0.00852)	
Observations	6904		6872		6904	

Appendix 8h: Mixed effects models explaining simulated outcome variables for Very Deep Vertisol soils; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha		Total ESS value in INR/ha		Net profit by evapo-transpiration in INR/m³	
	coef.	rank	coef.	rank	coef.	rank
Year of cultivation	-497.3*** (15.51)		-435.8*** (15.77)		-0.0330*** (0.00182)	
Management Parameters						
manure in kg	4.227*** (0.137)		4.417*** (0.139)		0.000400*** (0.000016)	
fertilizer in kg	196.8*** (5.289)		166.8*** (5.366)		0.0227*** (0.000622)	
irrigation in mm	-4.341 (2.567)		-7.159** (2.581)		-0.00101** (0.000316)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	125223.7*** (4962)	5	107076.8*** (4615)	6	8.834*** (1.217)	5
Maize-Chickpea	130406.0*** (4973)	3	117602.5*** (4627)	4	8.511*** (1.217)	6
Sorghum-Fallow	45166.6*** (4977.9)	11	40028.7*** (4632.1)	10	7.119*** (1.218)	8
Sorghum-Wheat	61551.5*** (4959.1)	10	34368.5*** (4611.7)	11	-0.926 (1.216)	11
Millet-Sorghum	70979.0*** (4948.4)	8	57184.8*** (4599.9)	9	4.834*** (1.216)	9
Mungbean- Sorghum	120969.1*** (4945)	6	108699.1*** (4596)	5	10.56*** (1.216)	3
Pigeonpea-Fallow	69517.1*** (4969.8)	9	71742.2*** (4623.0)	8	14.27*** (1.217)	1
Rice-Chickpea	136631.1*** (5120)	2	122080.8*** (4785)	2	7.163*** (1.227)	7
Soybean-Chickpea	126676.5*** (4963)	4	119626.8*** (4617)	3	9.474*** (1.217)	4
Sorghum- Chickpea	165753.9*** (4963)	1	153473.3*** (4616)	1	11.23*** (1.217)	2
Soybean-Maize	90890.1*** (4960.2)	7	80274.3*** (4612.9)	7	4.671*** (1.216)	10
Climate variables						
Average minimum temperature in °C	2026.1*** (123.6)		1838.7*** (125.7)		0.116*** (0.0145)	
August rainfall in mm	12.56*** (0.793)		12.65*** (0.806)		0.00114*** (0.0000931)	
Number of annual rainy days	244.7*** (8.950)		271.2*** (9.102)		0.0308*** (0.00105)	
Consecutive dry days during monsoon	186.5*** (21.97)		249.5*** (22.35)		0.0407*** (0.00258)	
solar radiation	5871.6*** (187.0)		4813.1*** (190.2)		0.0350 (0.0219)	
Constant	825309.2*** (29494.9)		713754.4*** (29979.0)		66.06*** (3.495)	
Random-effects parameters						
Cropping system	8.391*** (0.186)		8.317*** (0.186)		0.0829 (0.183)	
Residual	10.25*** (0.00235)		10.26*** (0.00236)		1.196*** (0.00235)	
Observations	90264		89681		90264	

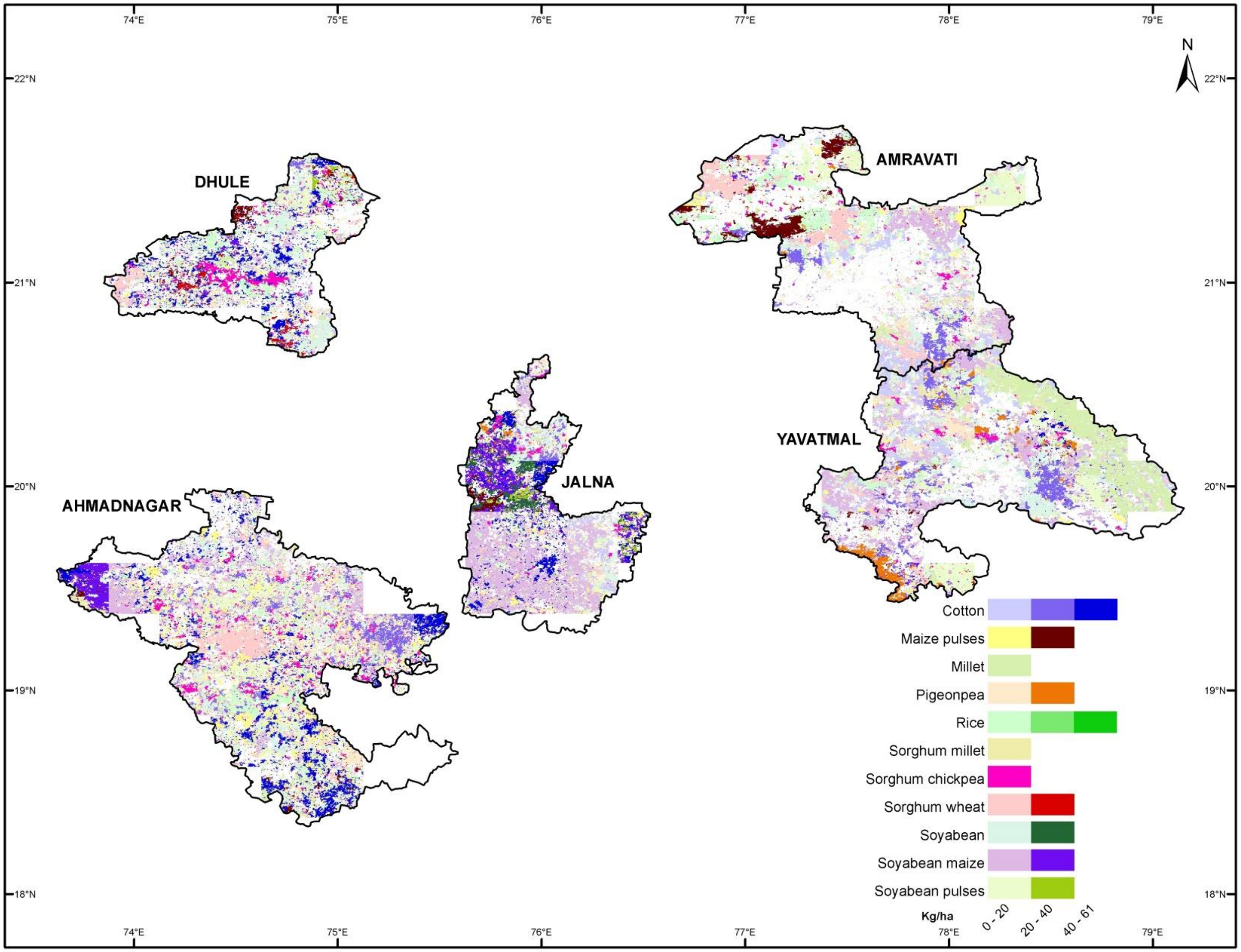
Appendix 8i: Mixed effects models explaining simulated outcome variables for Very Shallow Entisol soils; (coefficients with standard errors clustered by groups in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01)

	Net profit in INR/ha		Total ESS value in INR/ha		Net profit by evapo-transpiration in INR/m^3	
	coef.	rank	coef.	rank	coef.	rank
Year of cultivation	-31.40** (9.961)		6.940 (10.94)		0.00988*** (0.00179)	
Management Parameters						
manure in kg	0.810*** (0.0900)		0.723*** (0.0987)		0.000105*** (0.00002)	
fertilizer in kg	96.75*** (3.517)		64.09*** (3.858)		0.0129*** (0.000631)	
irrigation in mm	37.36*** (1.628)		44.96*** (1.816)		0.00664*** (0.000295)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	-26303*** (4593)	11	-32831*** (7413)	7	-6.246*** (0.97)	10
Maize-Chickpea	-3847.4 (4592)		-24366** (7412)	6	-3.120** (0.968)	6
Sorghum-Fallow	8416.4 (4594.8)		3170.4 (7414.6)		0.139 (0.968)	
Sorghum-Wheat	-7569.9 (4591)		-38172*** (7412)	9	-4.314*** (0.97)	7
Millet-Sorghum	-20197*** (4586)	8	-34857*** (7408)	8	-4.969*** (0.97)	8
Mungbean- Sorghum	16553*** (4585)	2	2734.9 (7406.9)		-0.515 (0.967)	
Pigeonpea-Fallow	40780*** (4596)	1	44628*** (7416)	1	8.004*** (0.968)	1
Rice-Chickpea	-24420*** (4702)	10	-65232*** (7498)	11	-7.939*** (0.99)	11
Soybean-Chickpea	-5502.3 (4588)		-18827.5* (7410)	4	-3.032** (0.967)	5
Sorghum- Chickpea	2069.6 (4587.6)		-20462** (7409)	5	-2.466* (0.967)	4
Soybean-Maize	-22290*** (4592)	9	-38874*** (7413)	10	-5.380*** (0.97)	9
Climate variables						
Average minimum temperature in ^{o}C	133.7* (63.48)		-285.7*** (69.68)		-0.00568 (0.0114)	
August rainfall in mm	5.465*** (0.557)		5.981*** (0.612)		0.00127*** (0.0001)	
Number of annual rainy days	195.0*** (5.772)		258.9*** (6.340)		0.0423*** (0.00104)	
Consecutive dry days during monsoon	-248.1*** (13.63)		-173.1*** (14.97)		-0.0444*** (0.00245)	
solar radiation	2194.4*** (139.4)		1026.9*** (153.0)		0.0822** (0.0250)	
Constant	12565.9 (18969.8)		-48834.0* (20966.0)		-20.88*** (3.411)	
Random-effects parameters						
Cropping system	8.317*** (0.193)		8.798*** (0.188)		-0.147 (0.190)	
Residual	9.471*** (0.00336)		9.562*** (0.00336)		0.845*** (0.00336)	
Observations	44406		44185		44406	

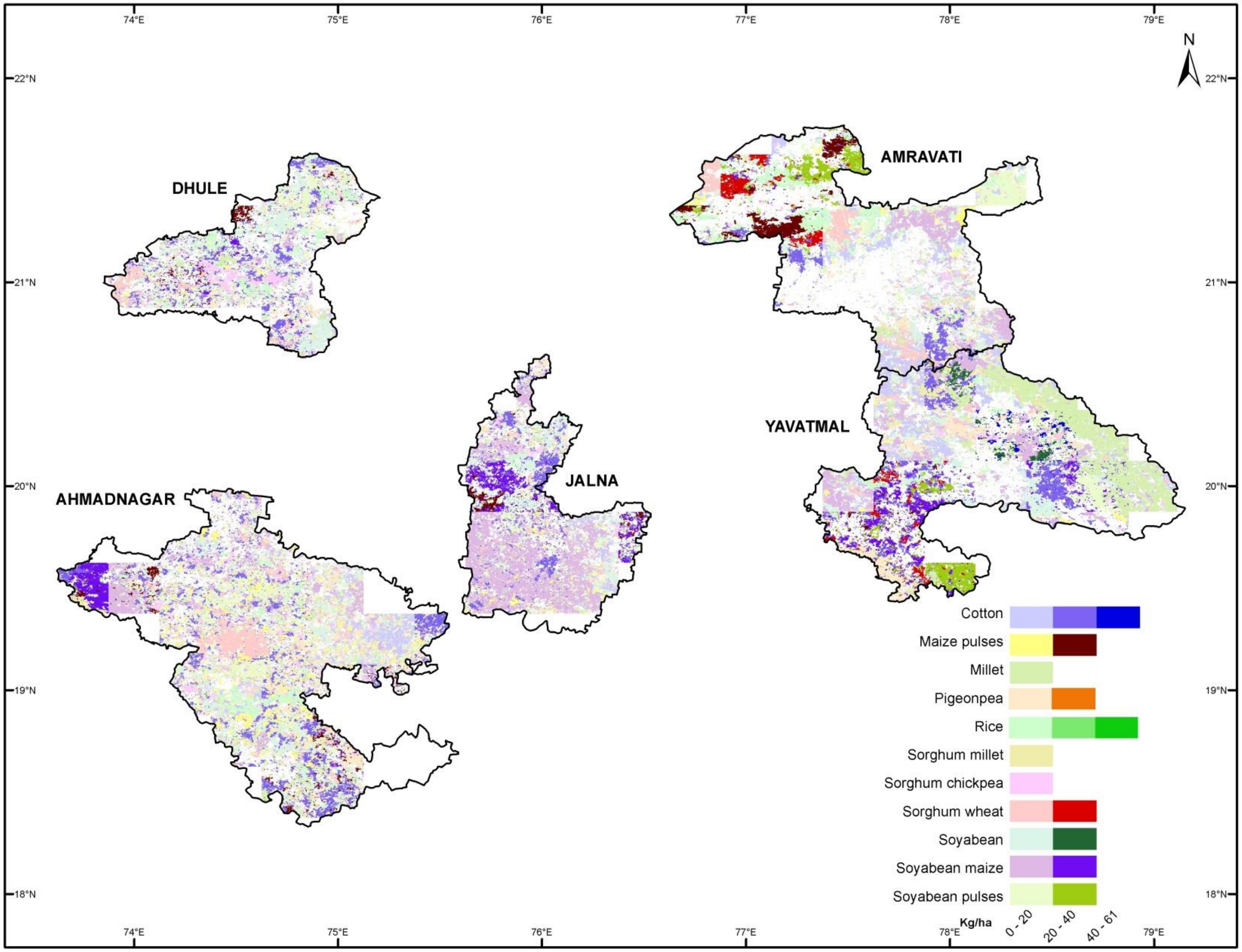
Appendix 8j: Mixed effects models explaining simulated outcome variables for Very Shallow Inceptisols soils; (coefficients with standard errors clustered by groups in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$)

	Net profit in INR/ha		Total ESS value in INR/ha		Net profit by evapo-transpiration in INR/m³	
	coef.	rank	coef.	rank	coef.	rank
Year of cultivation	125.5*** (26.85)		149.5*** (30.41)		0.0270*** (0.00474)	
Management Parameters						
manure in kg	0.956*** (0.195)		0.963*** (0.221)		0.000121*** (0.000034)	
fertilizer in kg	47.17*** (7.648)		10.99 (8.675)		0.00584*** (0.00135)	
irrigation in mm	34.34*** (3.365)		53.46*** (4.172)		0.00459*** (0.000583)	
Cropping systems (reference are Maize, Rice, Soybean, and Millet fallow systems)						
Cotton-Fallow	-17821.7*** (4944)	9	-22022.5* (9664.4)	7	-4.349*** (0.82)	10
Maize-Chickpea	-632.9 (4937.2)		-19925.5* (9657.3)	5	-1.940* (0.814)	5
Sorghum-Fallow	6080.7 (4950.5)		2835.8 (9670.2)		-0.105 (0.816)	
Sorghum-Wheat	-11724.8* (4932.6)	7	-43462.5*** (9653)	10	-3.317*** (0.81)	7
Millet-Sorghum	-16859.3*** (4911)	8	-31683.4** (9638.9)	8	-3.688*** (0.81)	8
Mungbean- Sorghum	18348.4*** (4905.1)	2	4225.4 (9634.9)		0.537 (0.808)	
Pigeonpea-Fallow	32145.9*** (4956.0)	1	37833.7*** (9673.9)	1	6.127*** (0.817)	1
Rice-Chickpea	-23677.1*** (5387)	11	-74790*** (10023)	11	-5.518*** (0.90)	11
Soybean-Chickpea	-3989.3 (4918.2)		-14999.3 (9647.1)		-2.155** (0.810)	6
Sorghum- Chickpea	-284.6 (4918.6)		-20978.2* (9645.4)	6	-1.880* (0.810)	4
Soybean-Maize	-18012.5*** (4940)	10	-35369.0*** (9658)	9	-3.825*** (0.81)	9
Climate variables						
Average minimum temperature in °C	-643.1*** (137.5)		-585.0*** (155.8)		-0.136*** (0.0243)	
August rainfall in mm	-0.799 (1.350)		-1.494 (1.528)		0.000830*** (0.000238)	
Number of annual rainy days	-22.04 (15.11)		2.331 (17.13)		-0.00215 (0.00267)	
Consecutive dry days during monsoon	-720.4*** (45.86)		-786.9*** (51.93)		-0.106*** (0.00809)	
solar radiation	1028.4** (351.1)		-210.3 (397.6)		0.0439 (0.0619)	
Constant	-244308.3*** (49418)		-285696.6*** (56093.2)		-48.75*** (8.718)	
Random-effects parameters						
Cropping system	8.379*** (0.234)		9.059*** (0.204)		-0.334 (0.214)	
Residual	9.275*** (0.00925)		9.396*** (0.00927)		0.632*** (0.00925)	
Observations	5867		5837		5867	

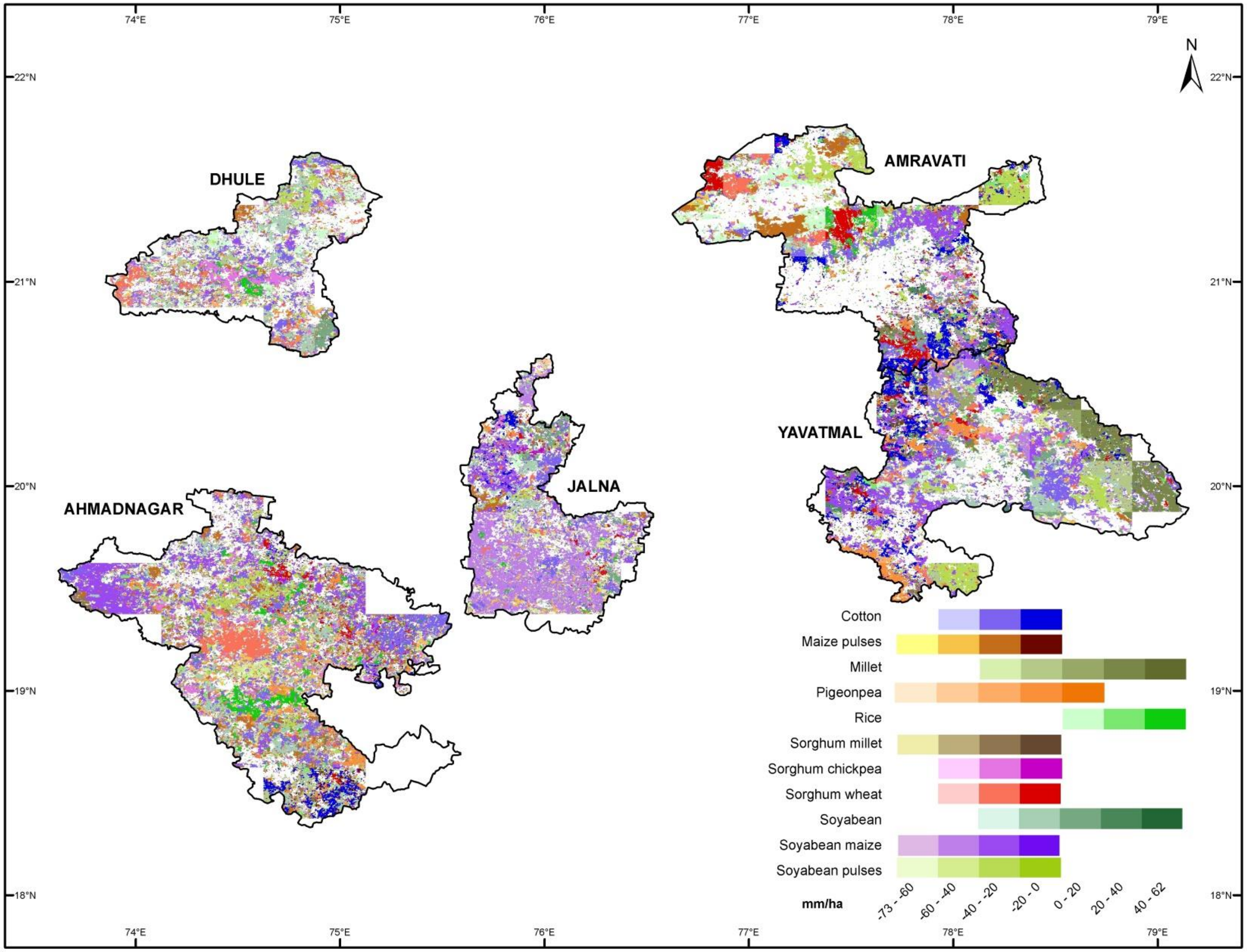
Appendix 9: Long term data on nitrate leaching (kg/ha) in response to farmers practices in various cropping systems



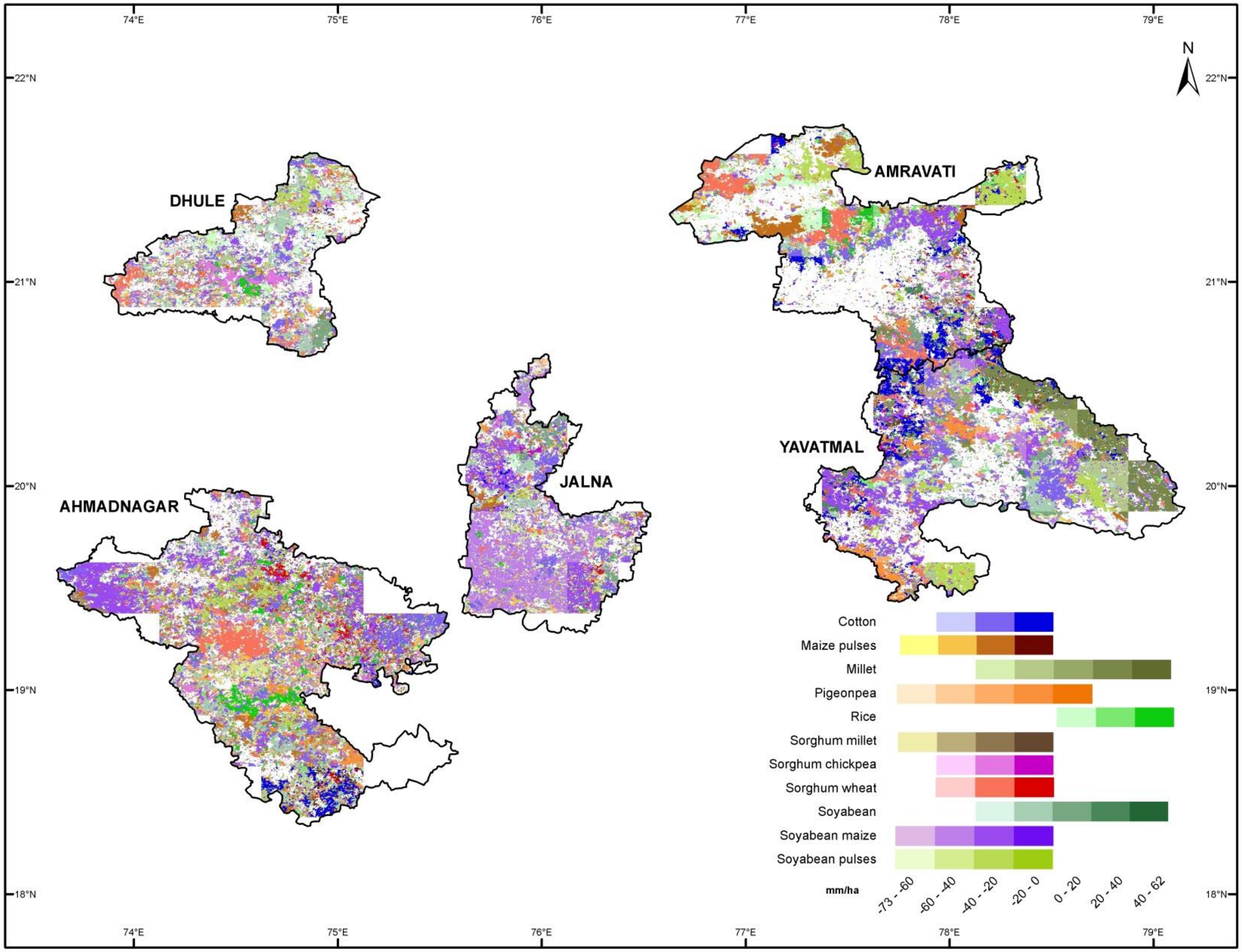
Appendix 10: Long term data on nitrate leaching (kg/ha) in response to recommended practices in various cropping systems



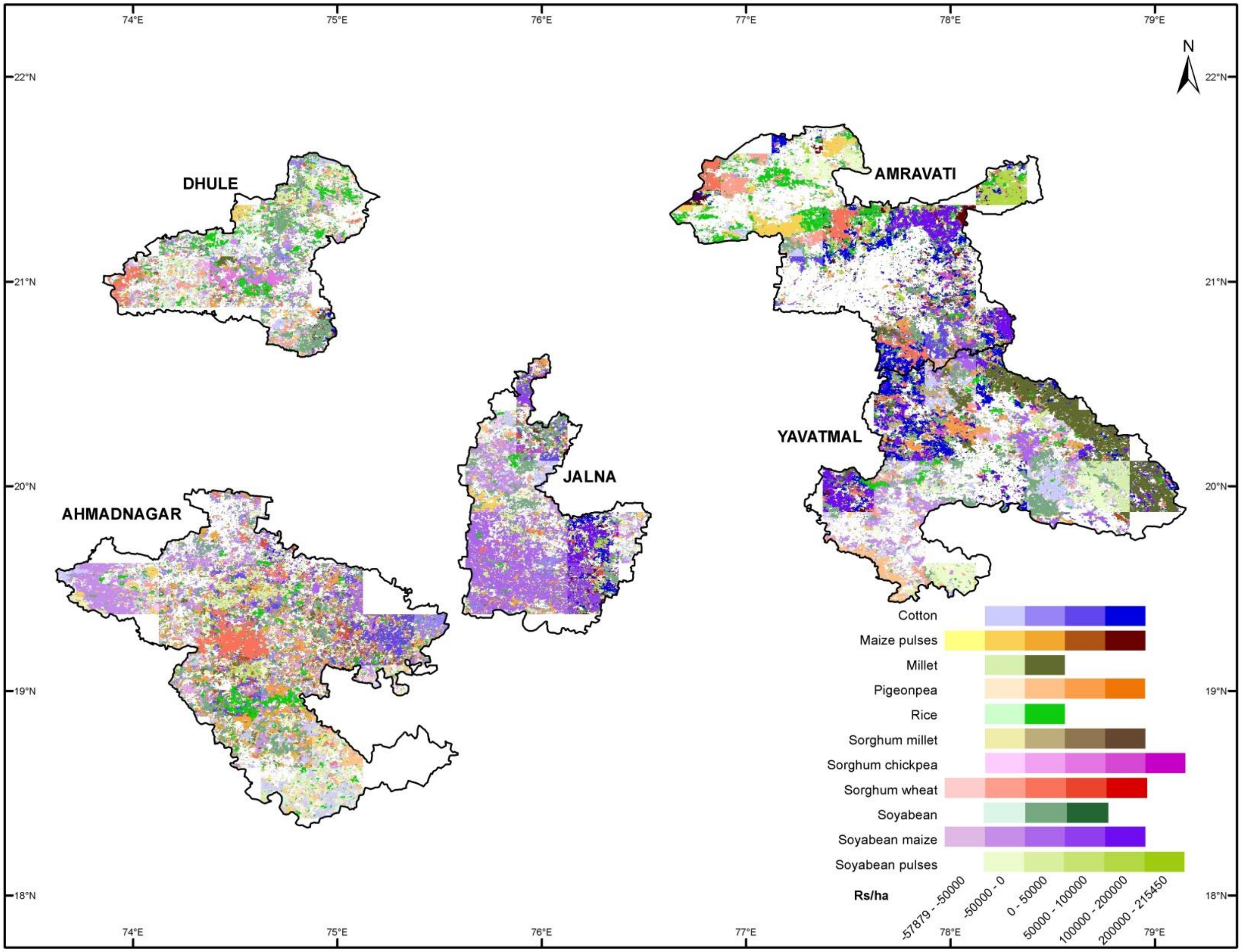
Appendix 11: Long term data on net water storage (mm) in response to farmers practices in various cropping systems



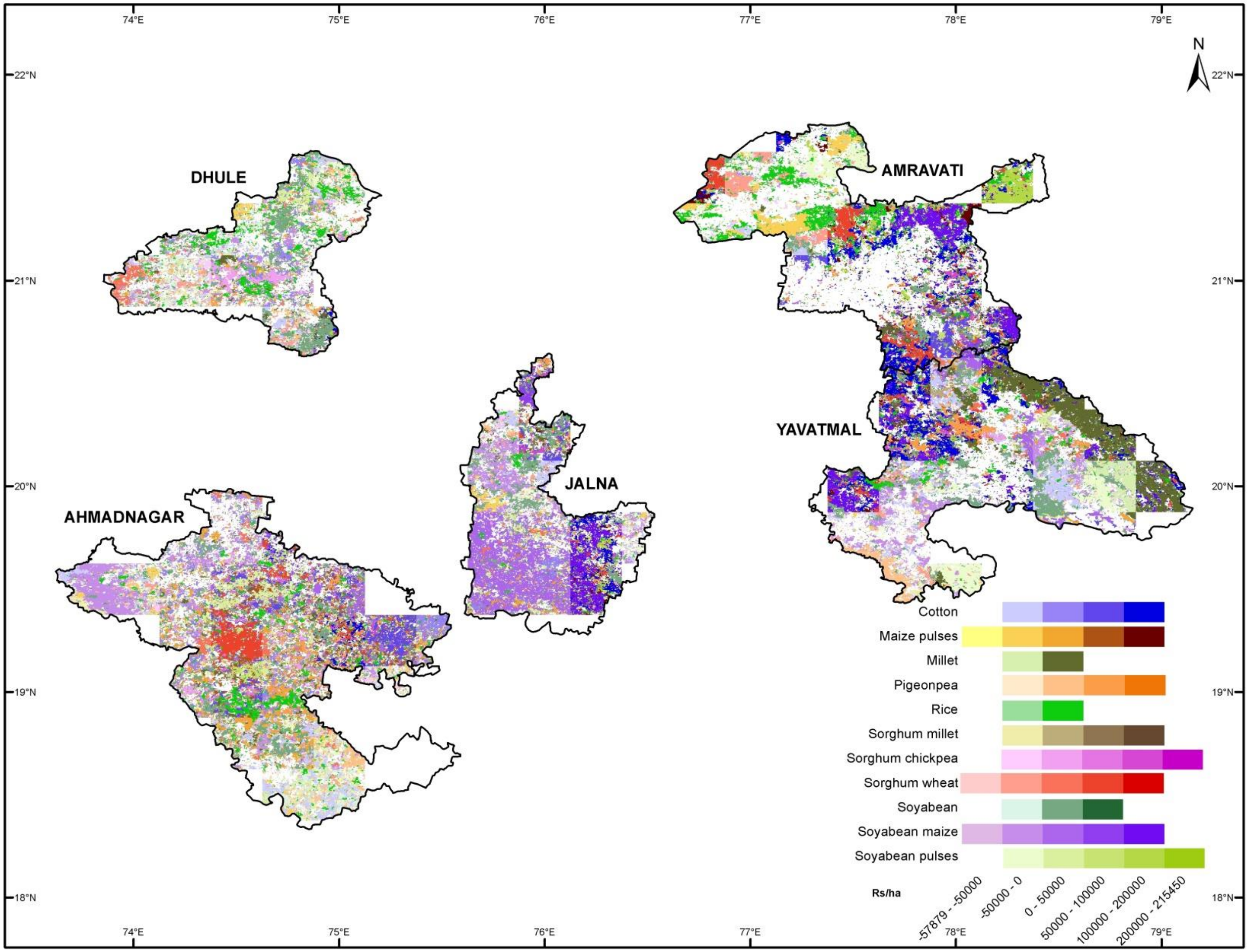
Appendix 12: Long term data on net water storage (mm) in response to recommended practices in various cropping systems



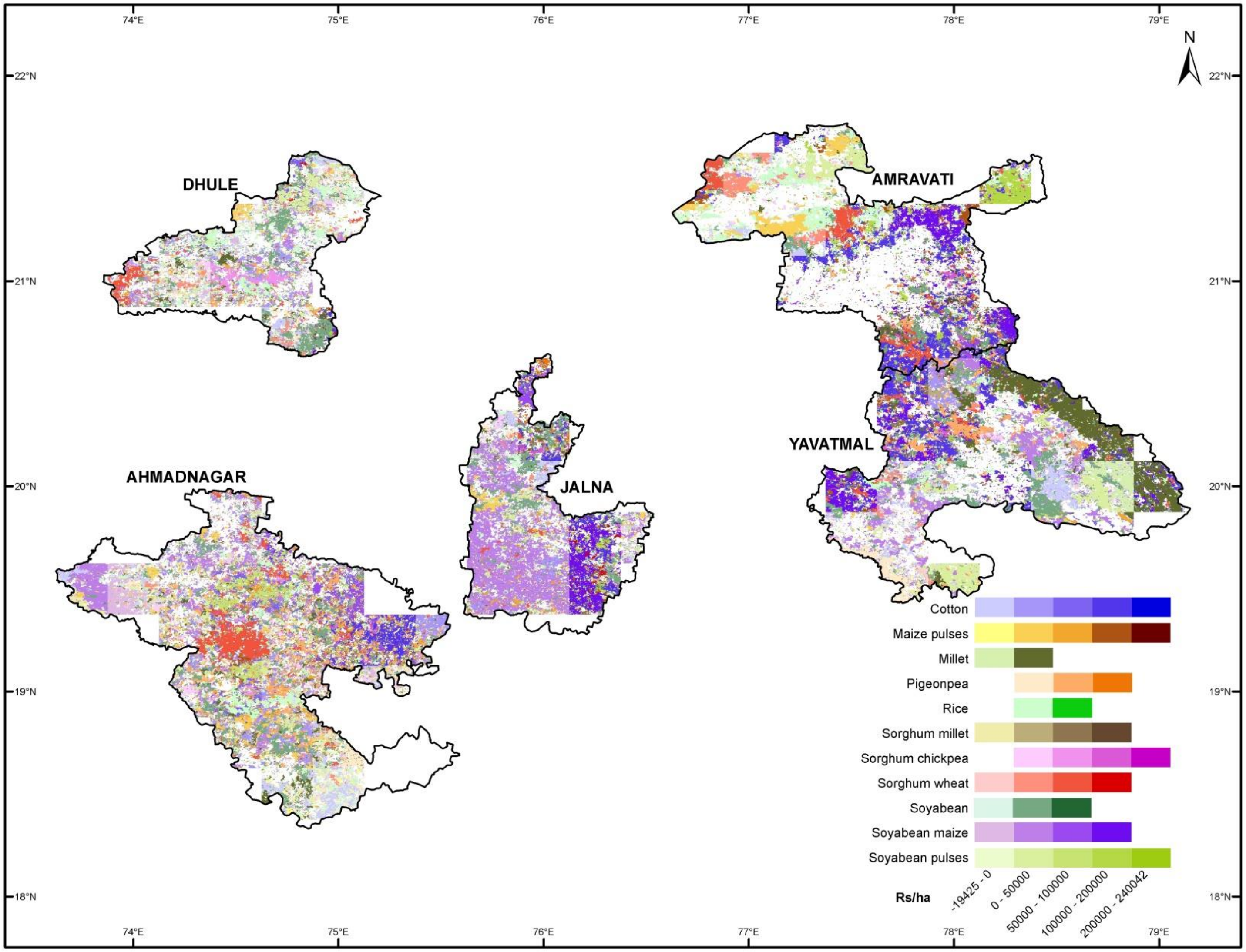
Appendix 13: Long term data on total ESS value in response to farmers practices in various cropping systems



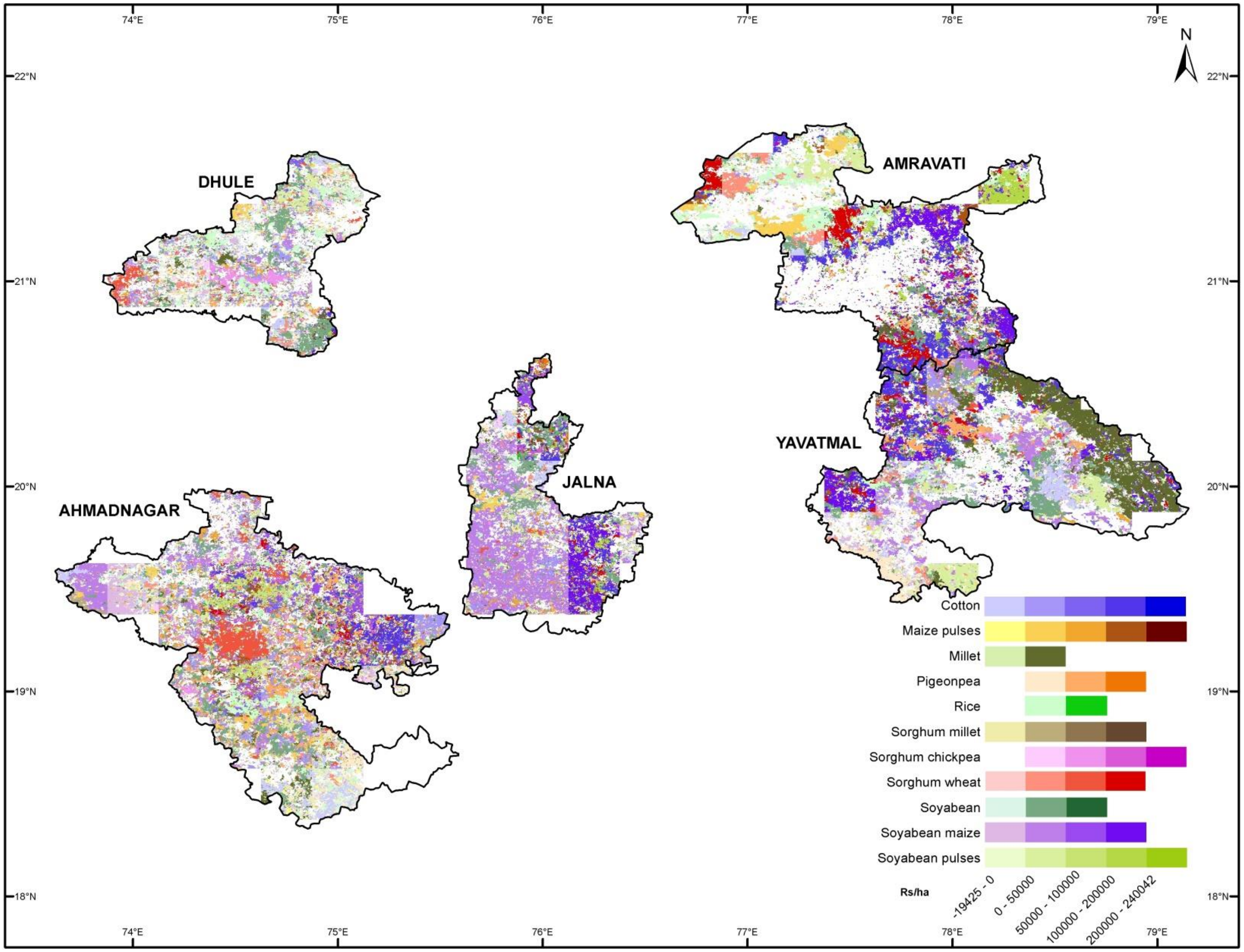
Appendix 14: Long term data on total ESS value in response to integrated practices in various cropping systems



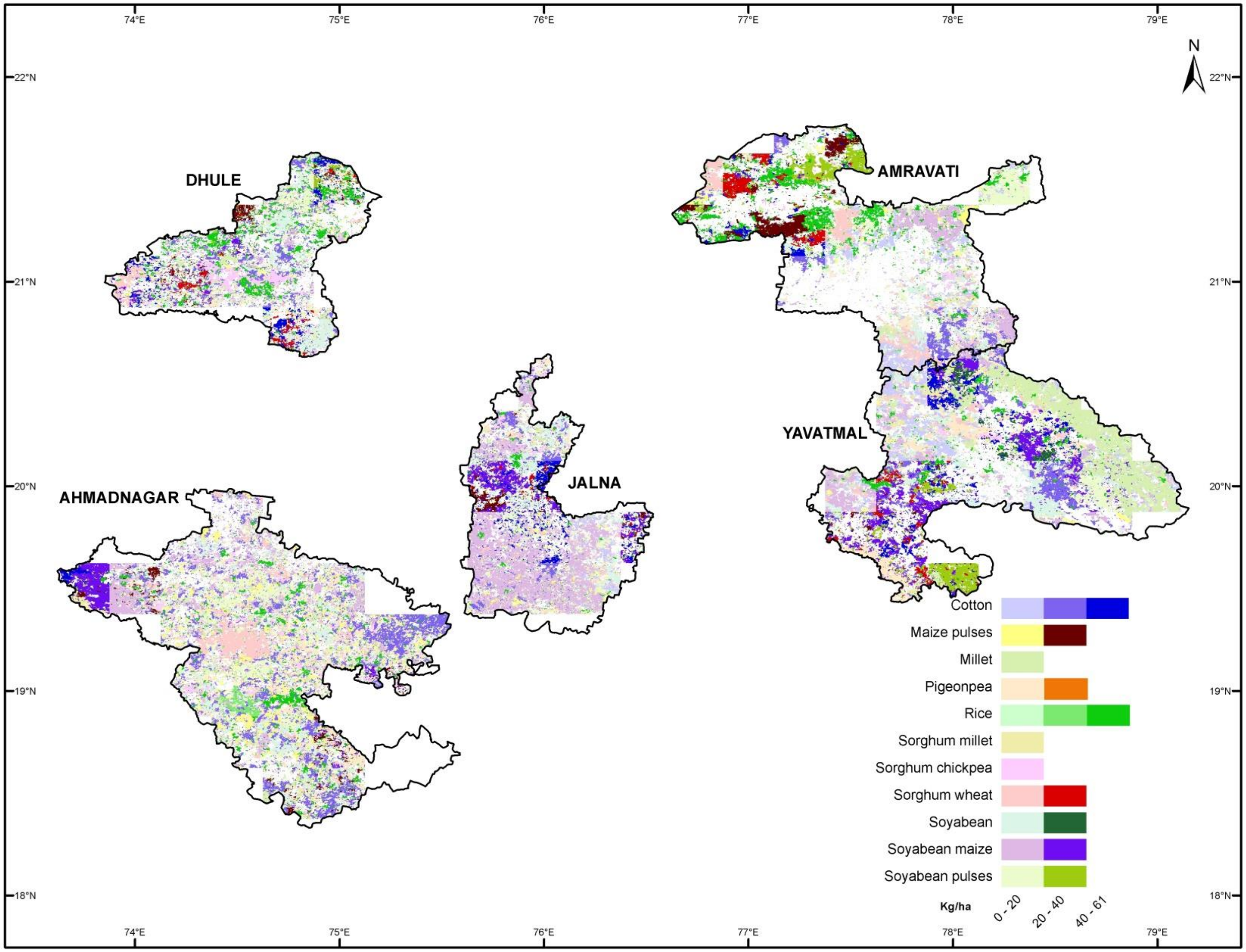
Appendix 15: Long term data on total profit in response to farmers practices in various cropping systems



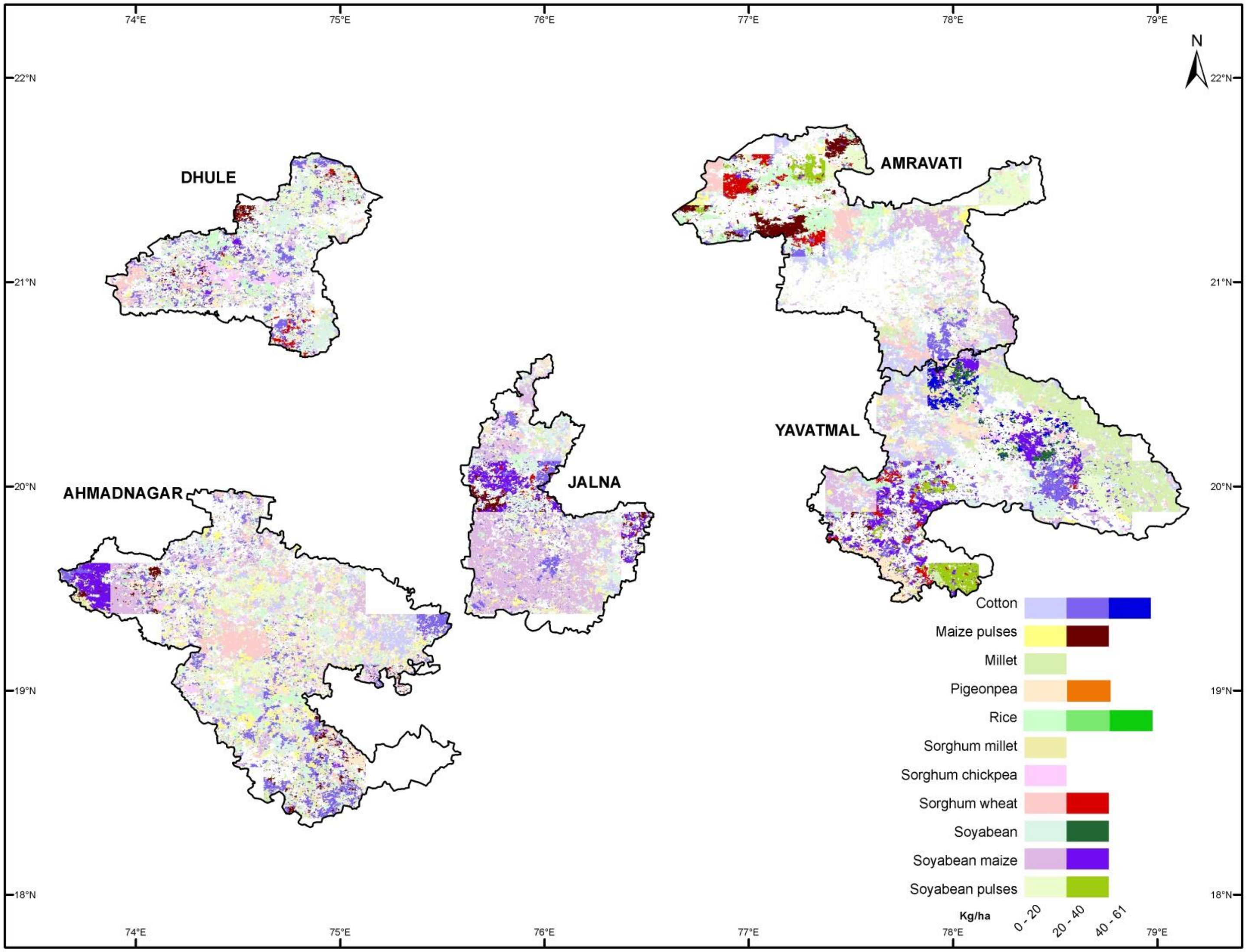
Appendix 16: Long term data on total profit in response to integrated practices in various cropping systems



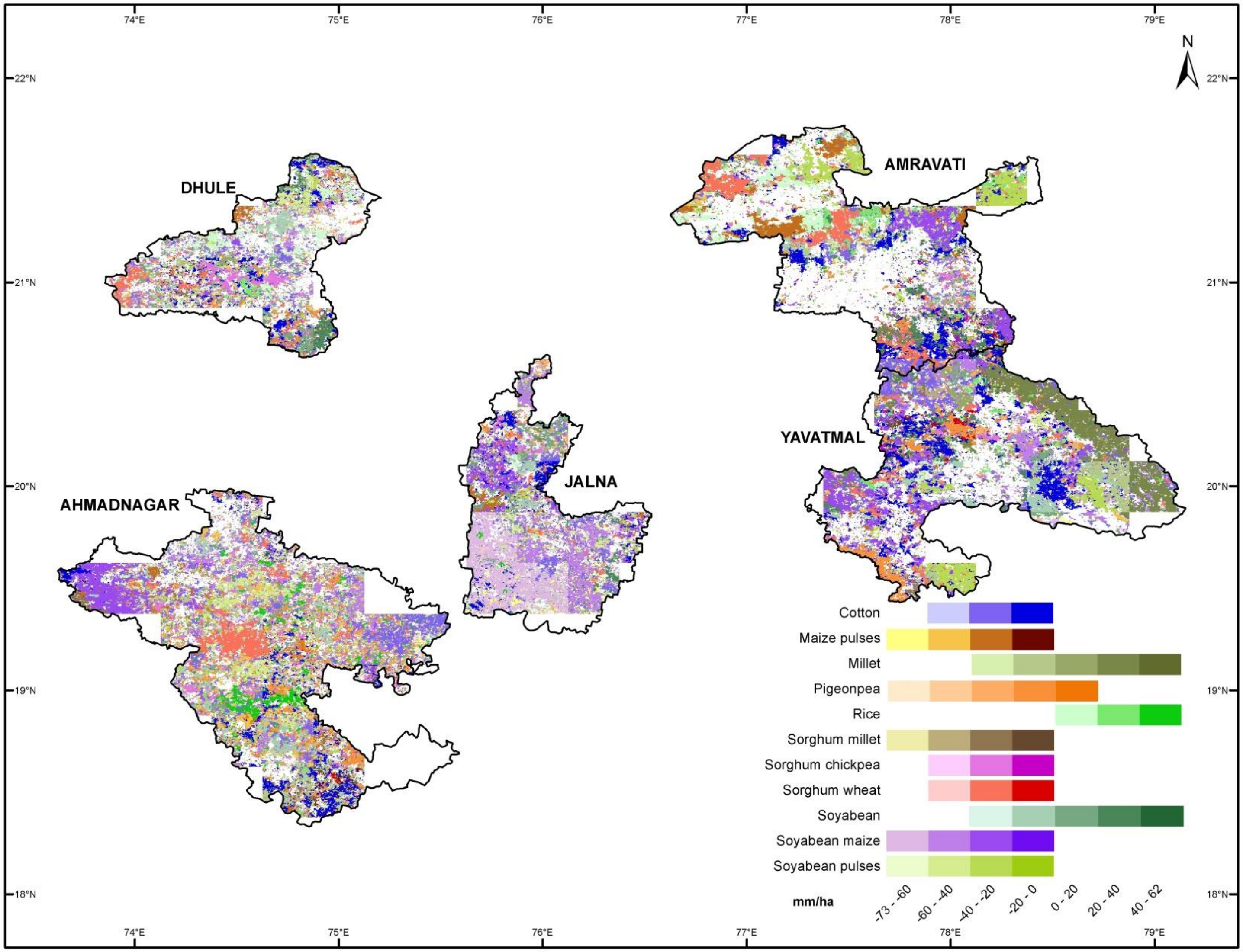
Appendix 17: Long term data on nitrogen leaching in response to integrated practices in various cropping systems under cool wet climate change scenario



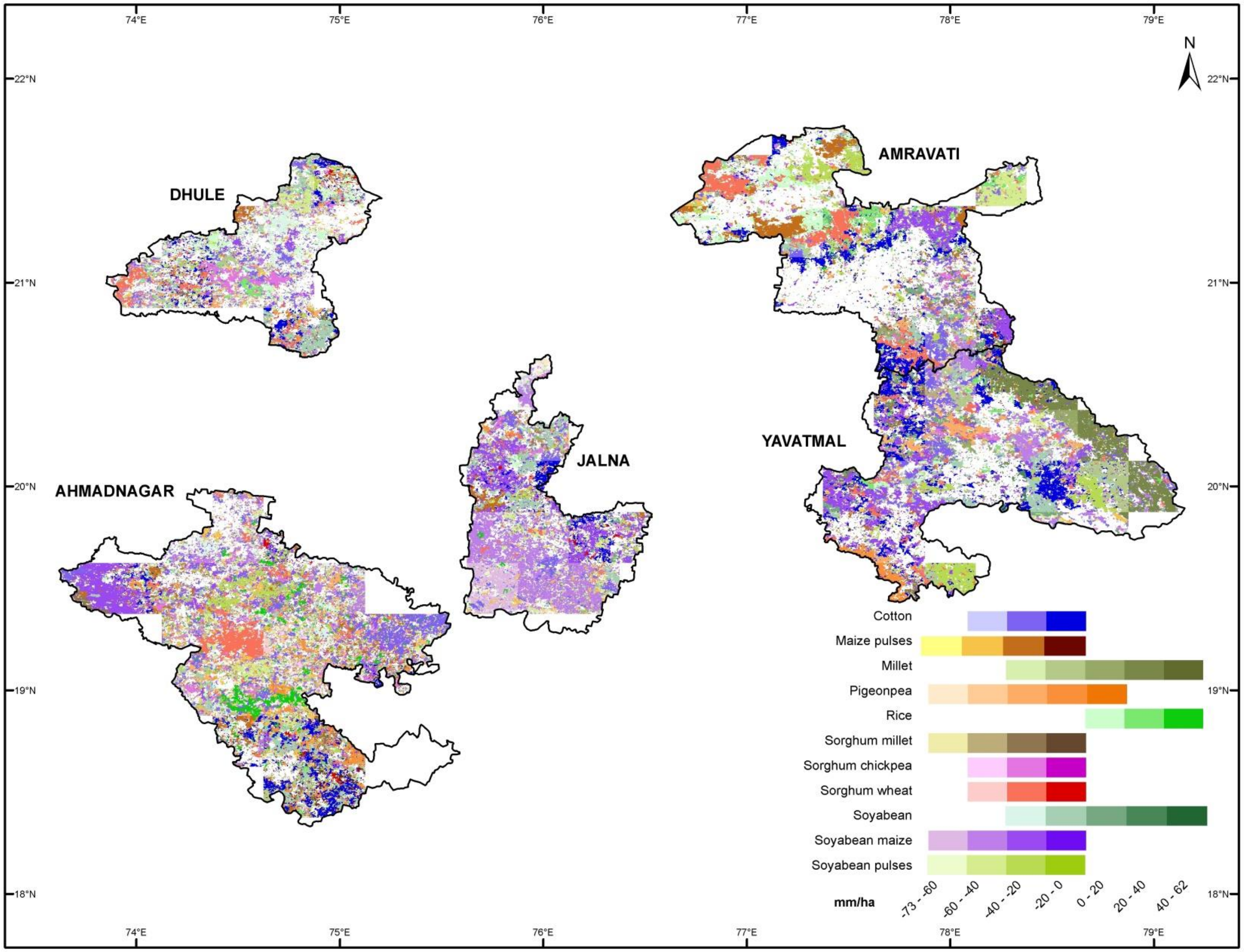
Appendix 18: Long term data on nitrogen leaching in response to integrated practices in various cropping systems under hot dry climate change scenario



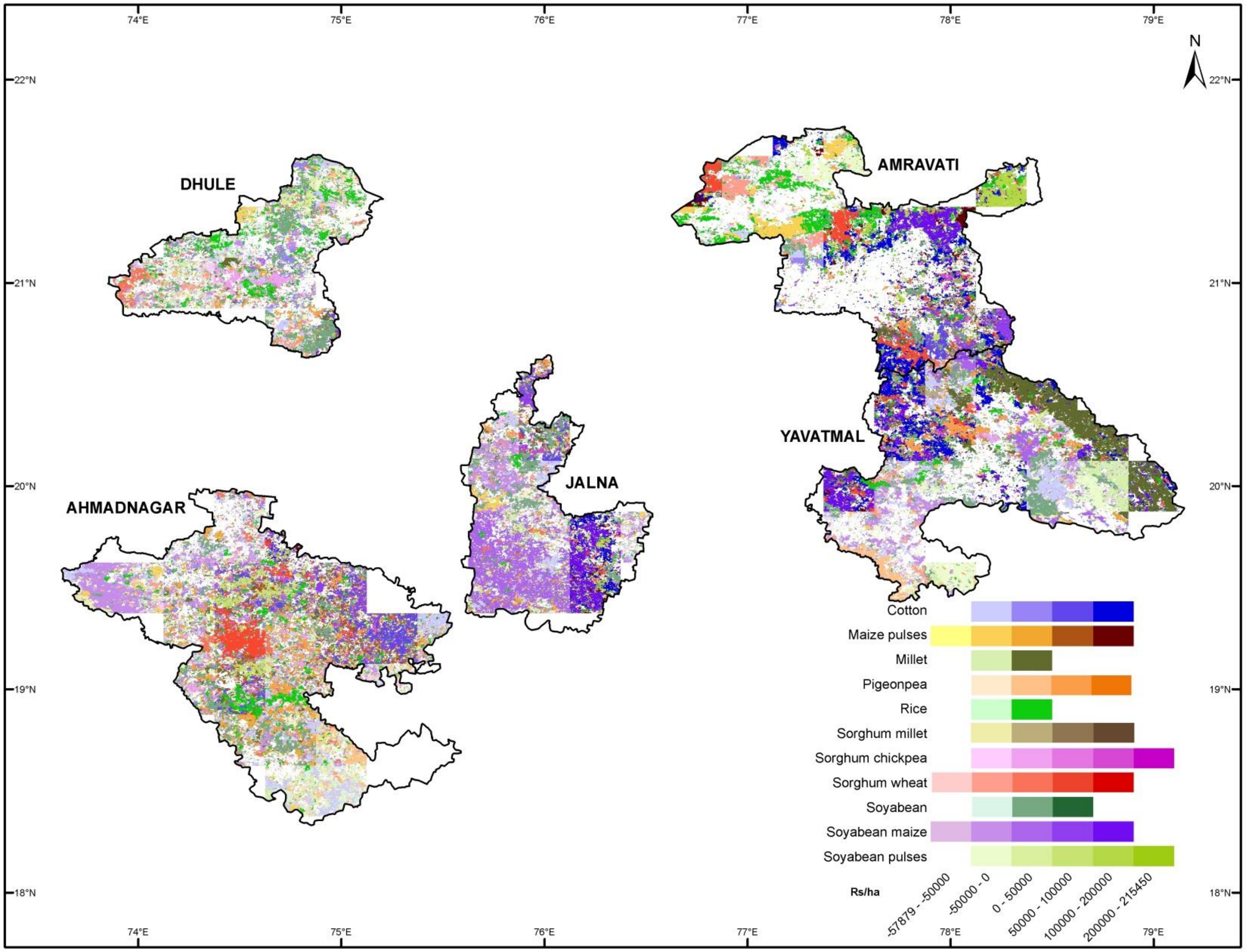
Appendix 19: Long term data on net water storage (mm) in response to integrated practices in various cropping systems under cool wet climate change scenario



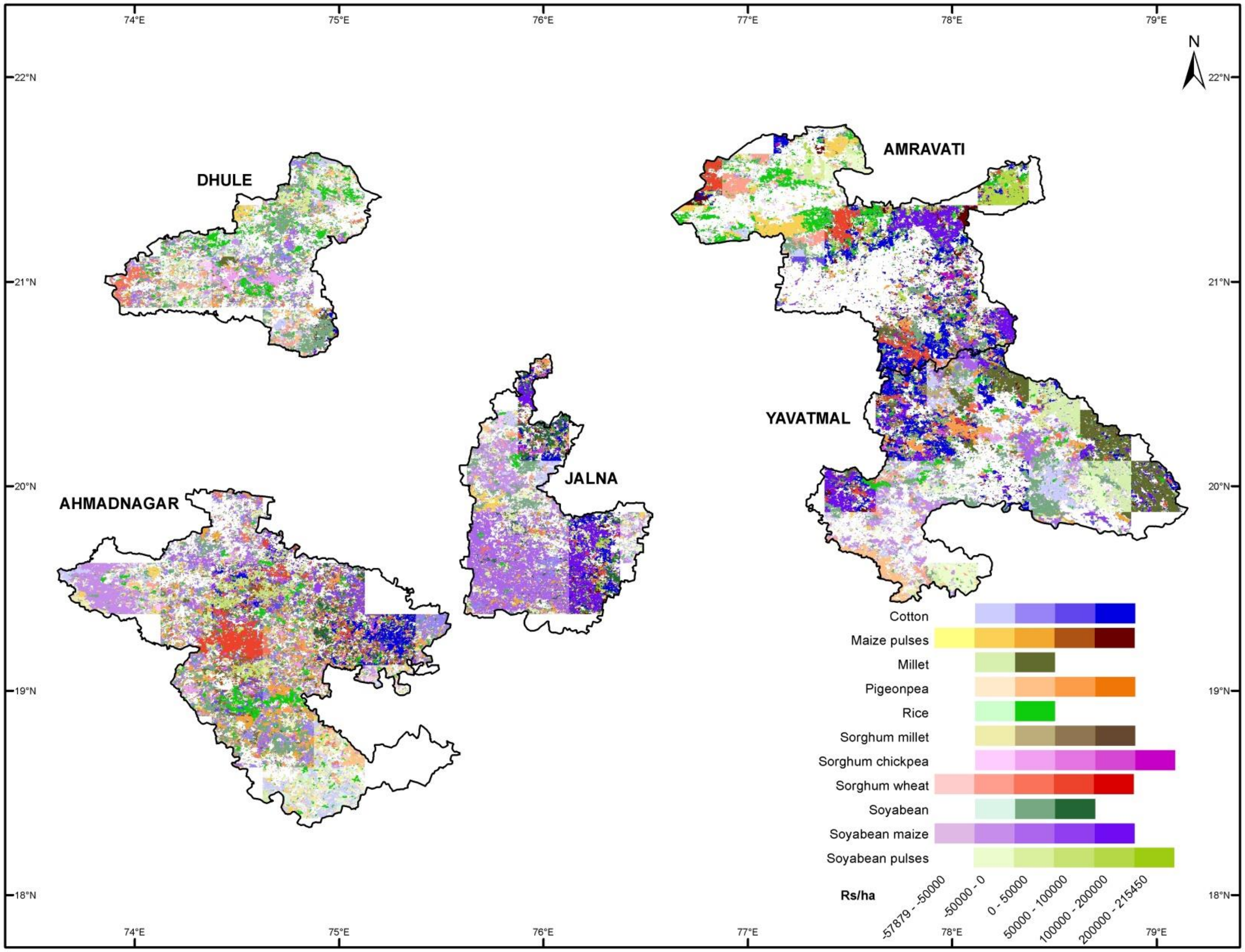
Appendix 20: Long term data on net water storage (mm) in response to integrated practices in various cropping systems under hot dry climate change scenario



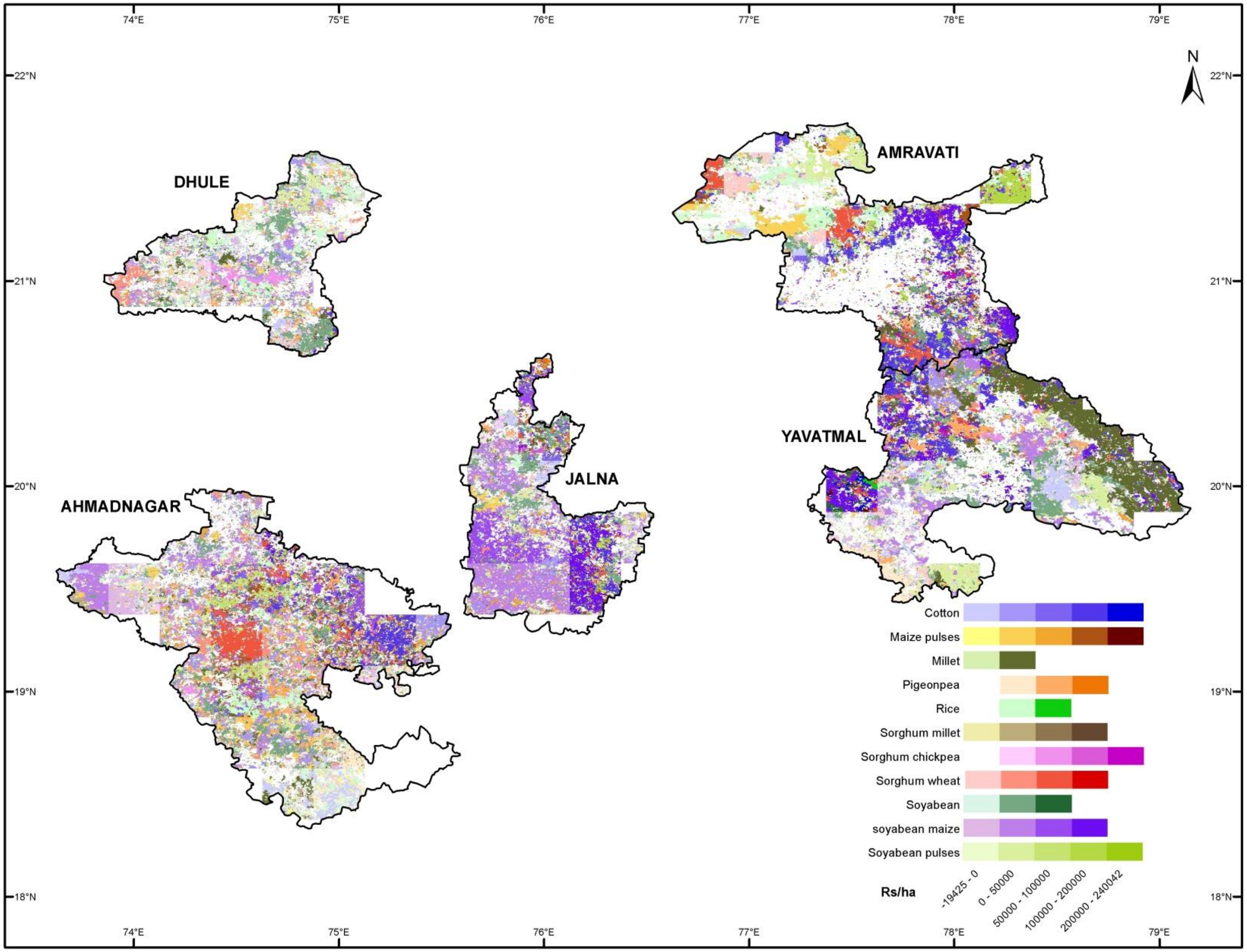
Appendix 21: Long term data on total ESS in response to integrated practices in various cropping systems under cool wet climate change scenario



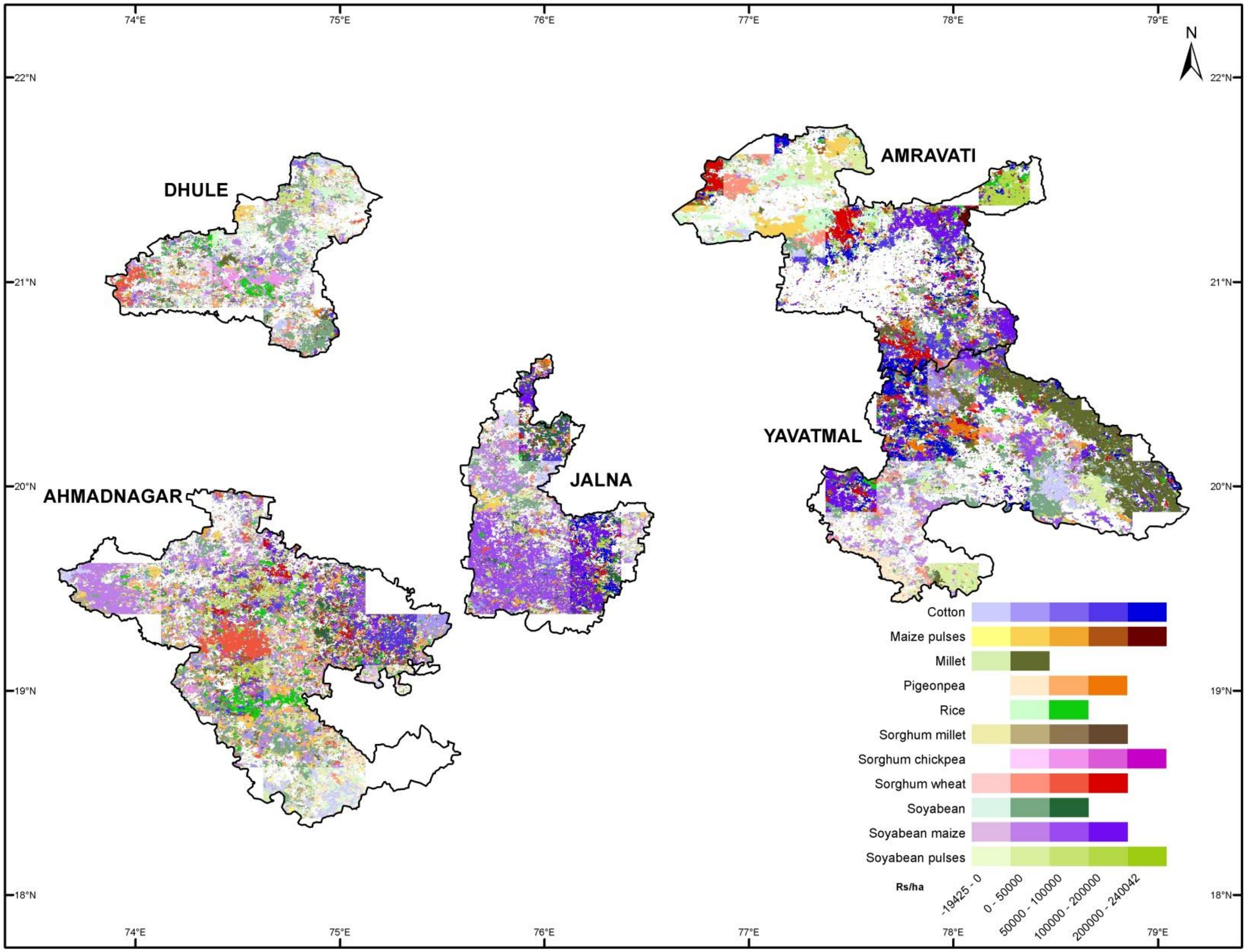
Appendix 22: Long term data on total ESS in response to integrated practices in various cropping systems under hot dry climate change scenario



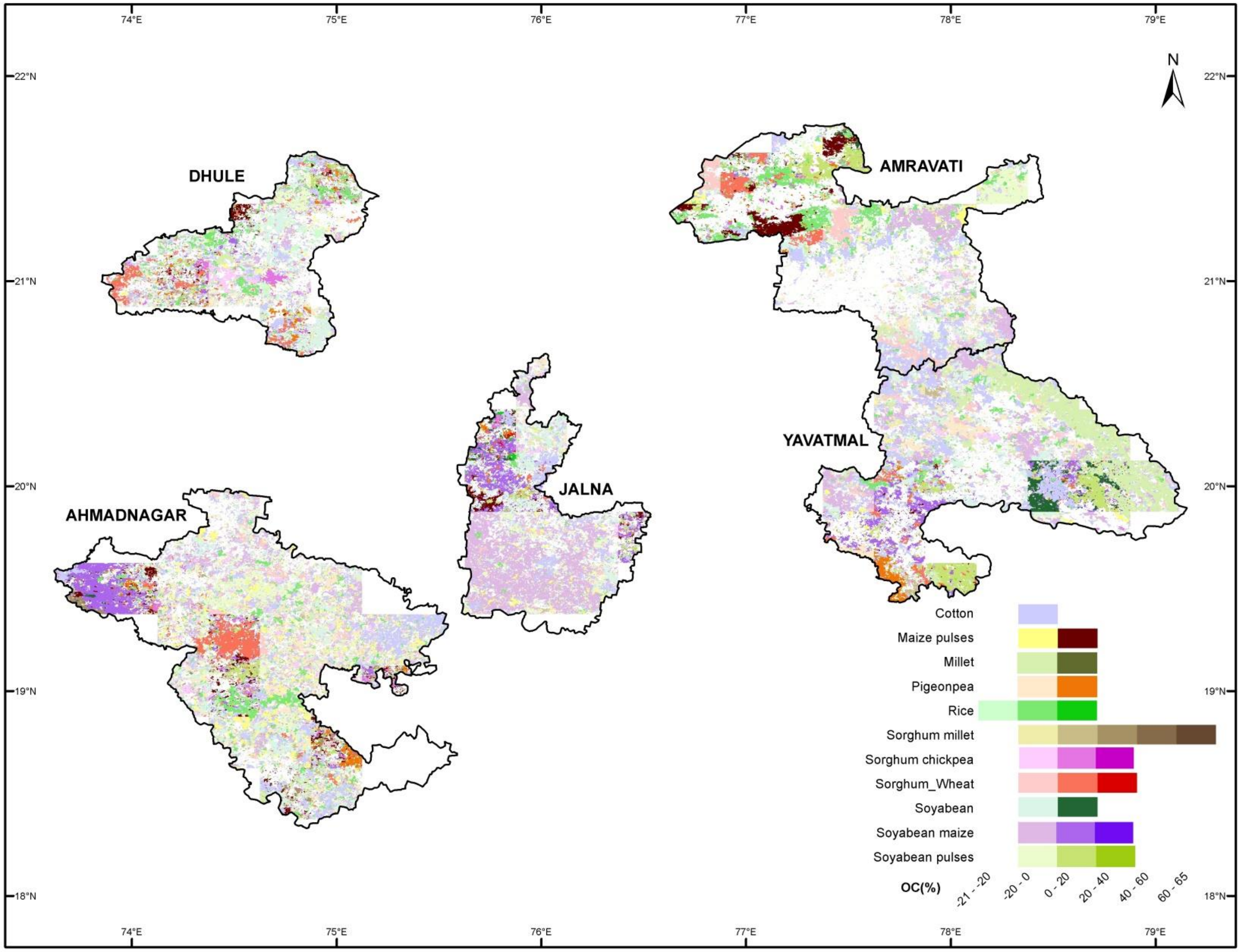
Appendix 23: Long term data on total profit in response to integrated practices in various cropping systems under cool wet climate change scenario



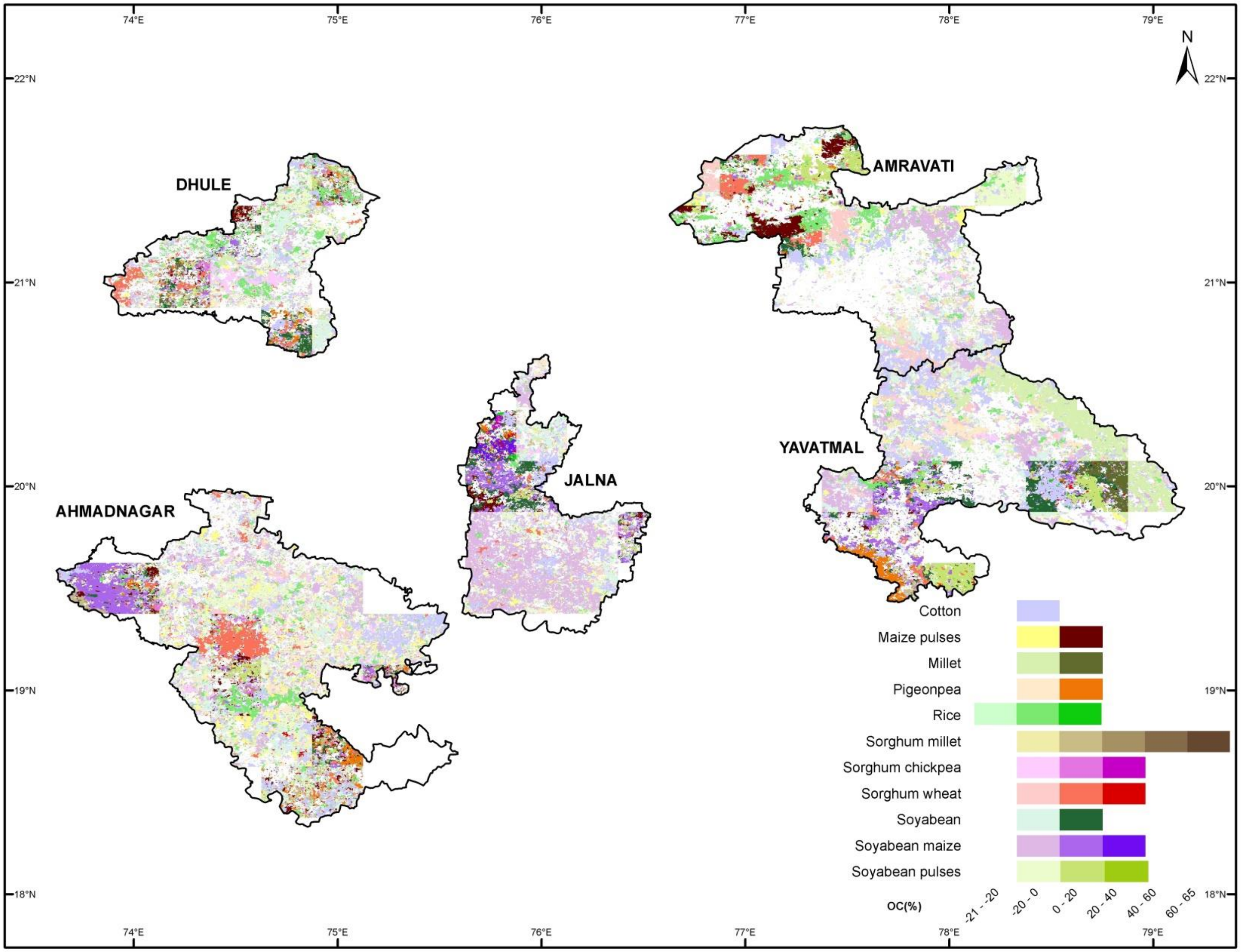
Appendix 24: Long term data on total profit in response to integrated practices in various cropping systems under hot dry climate change scenario



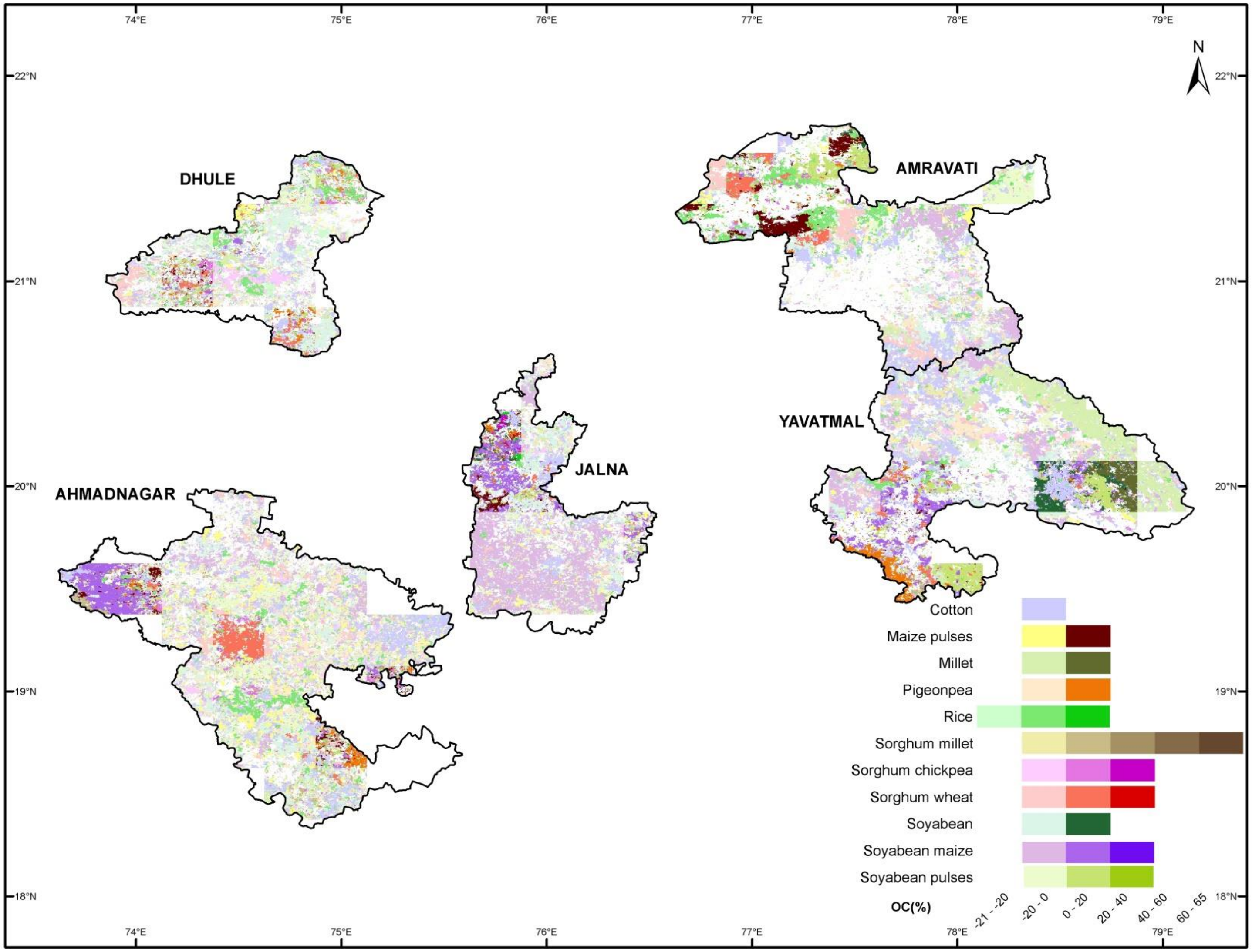
Appendix 25: Long term data on total organic carbon in response to farmers practices in various cropping systems



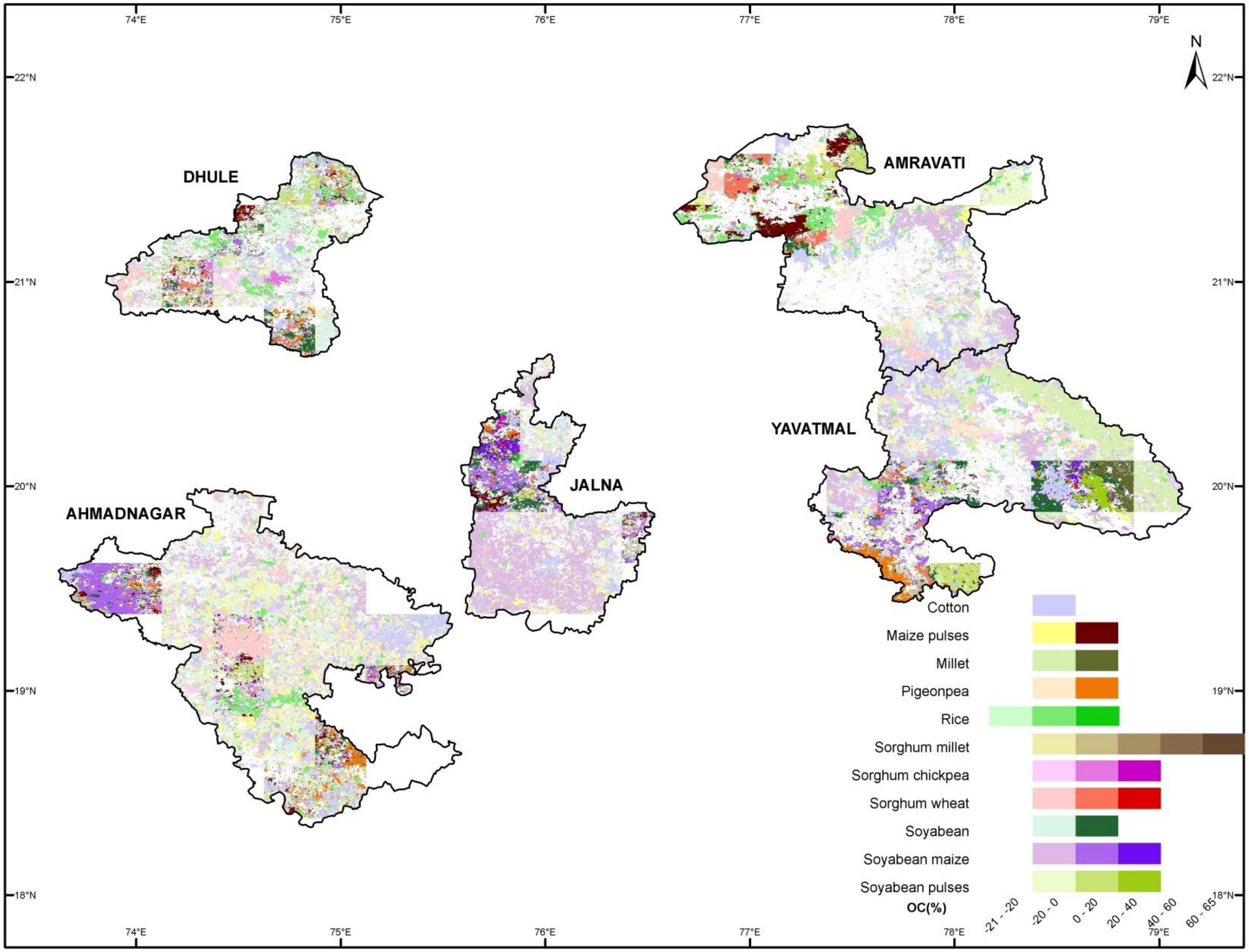
Appendix 26: Long term data on total organic carbon in response to integrated practices in various cropping systems



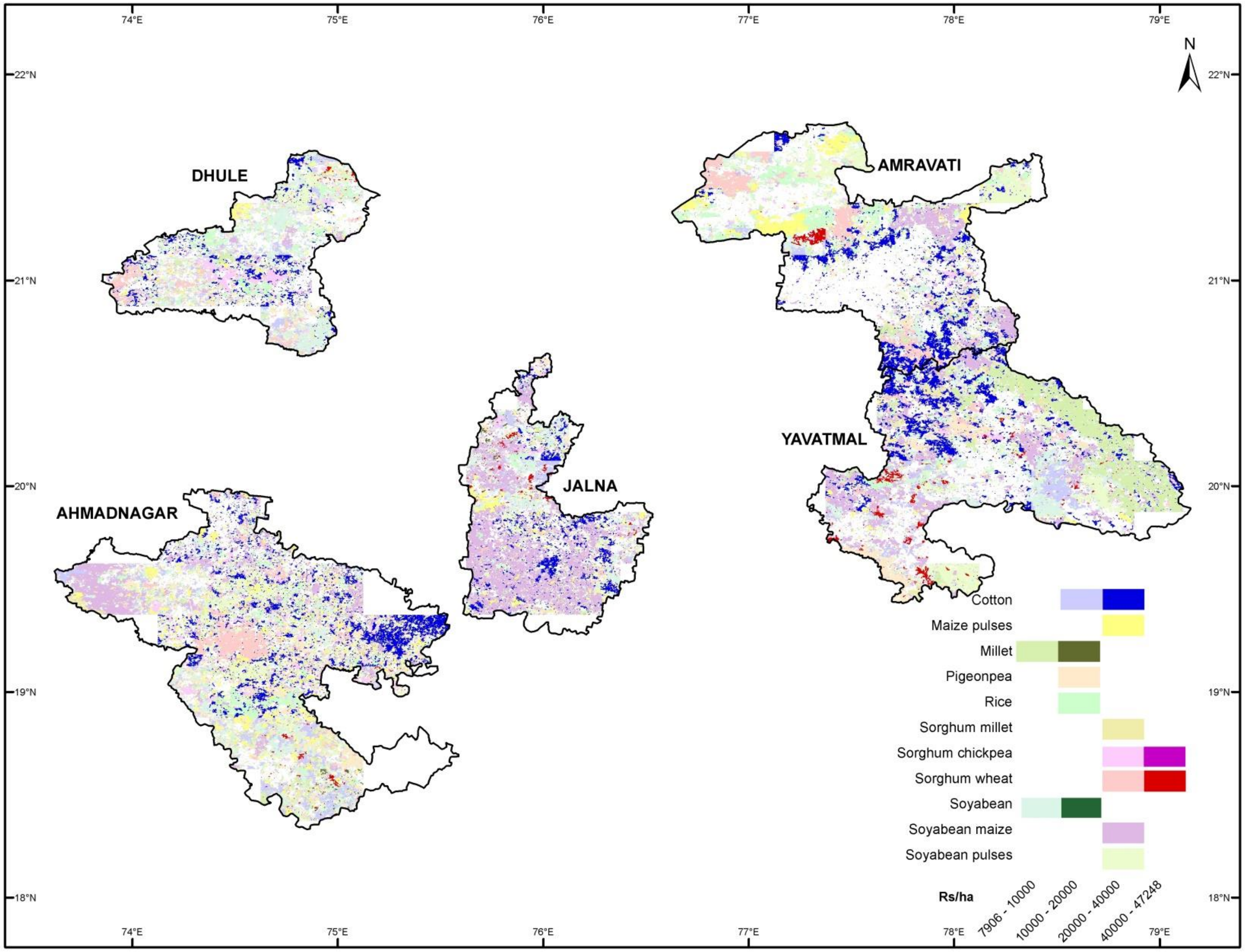
Appendix 27: Long term data on total organic carbon in response to integrated practices in various cropping systems under cool wet climate change scenario



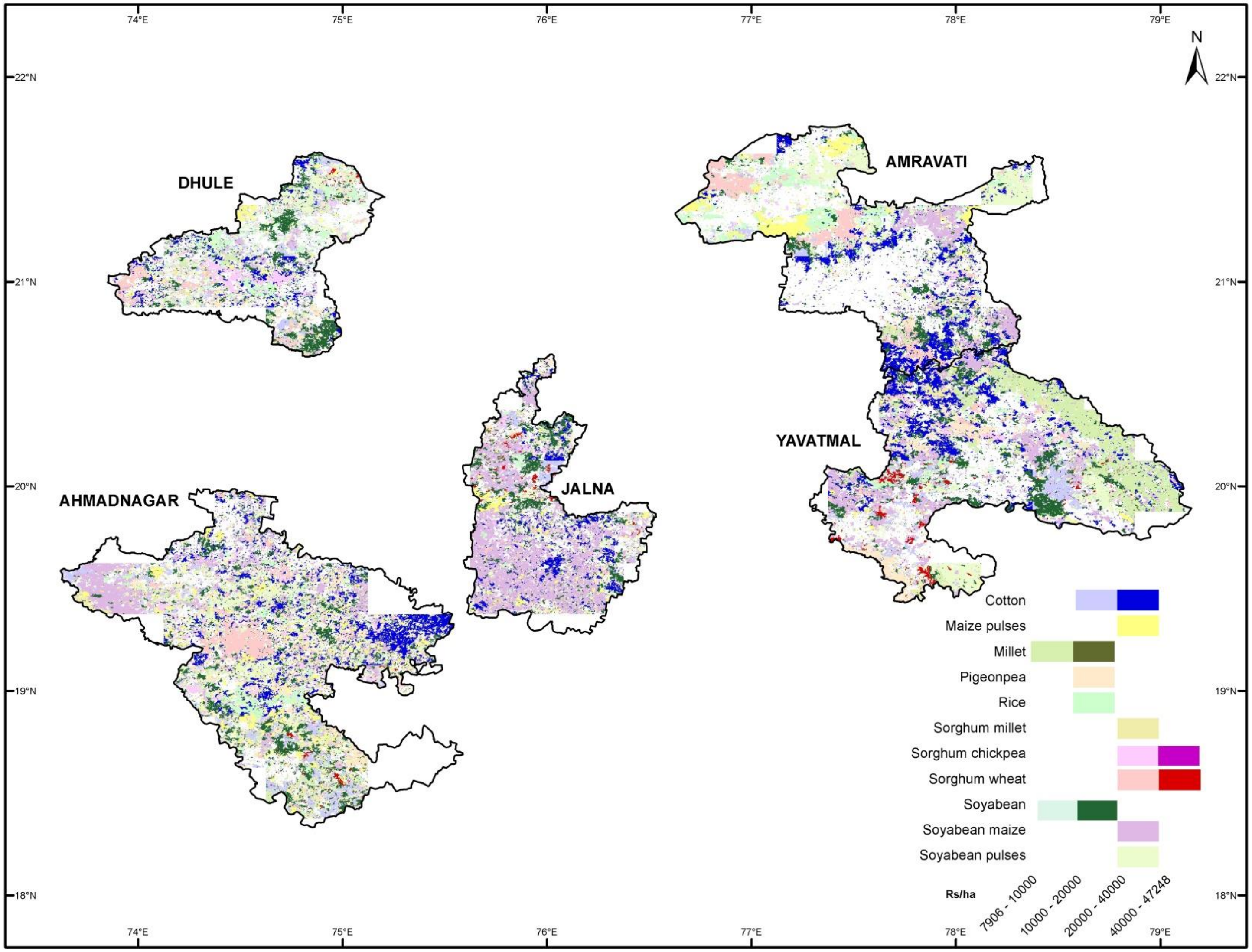
Appendix 28: Long term data on total organic carbon in response to integrated practices in various cropping systems under hot dry climate change scenario



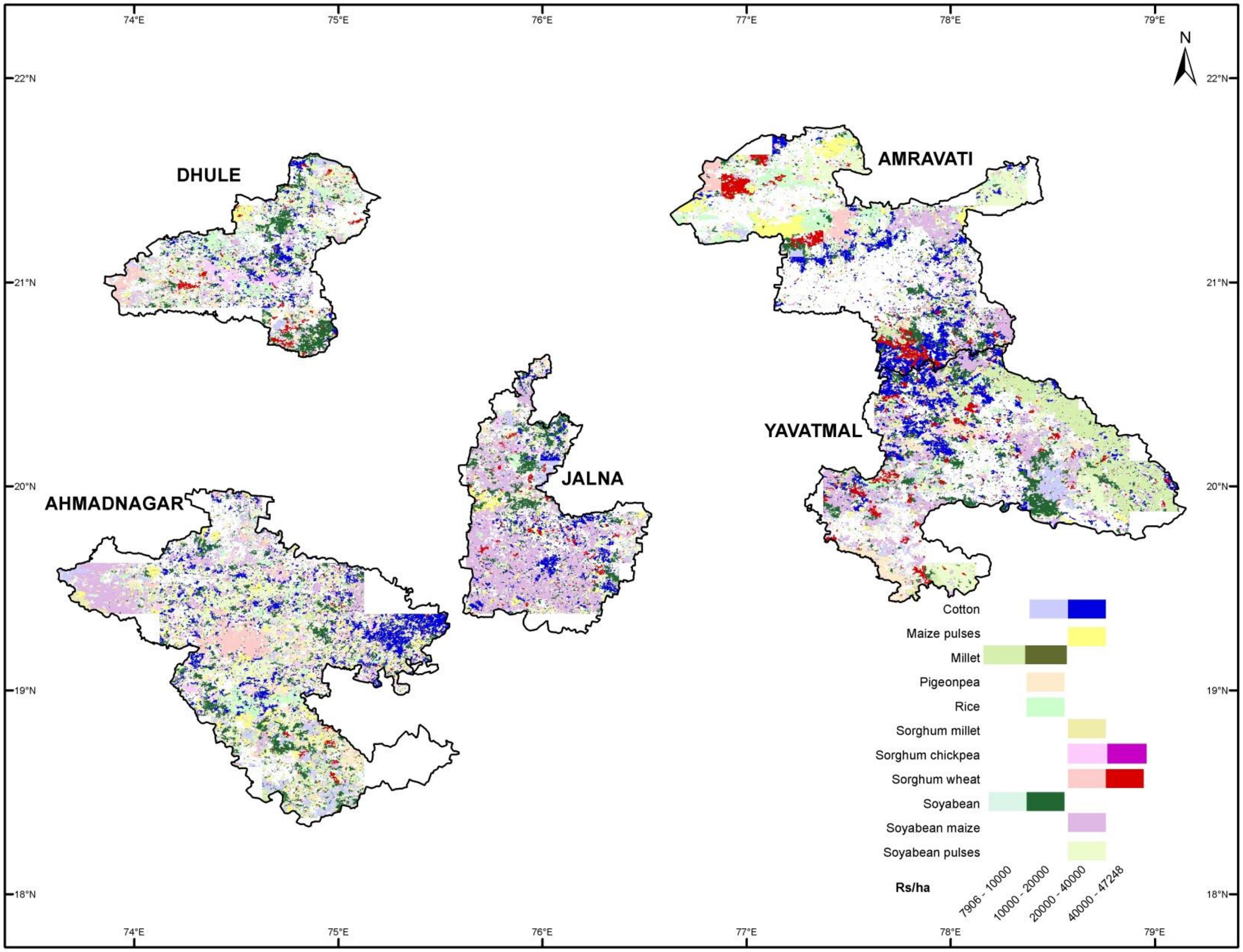
Appendix 29: Long term data on water consumption values (INR/ha) in response to farmers practices in various cropping systems



Appendix 30: Long term data on water consumption values (INR/ha) in response to integrated practices in various cropping systems



Appendix 31: Long term data on water consumption values (INR/ha) in response to integrated practices in various cropping systems under cool wet climate change scenario



Appendix 32: Long term data on water consumption values (INR/ha) in response to integrated practices in various cropping systems under hot dry climate change scenario