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Measuring Sustainable Intensification of Agricultural Productivity in Semi-Arid Tropics (SAT) of India – Case studies

Synthesis Report

D Kumara Charyulu, D Moses Shyam, K Dakshina Murthy, Gumma Murali Krishna, Cynthia Bantilan, S Nedumaran and Srigiri Srinivasa

INTERNATIONAL CROPS RESEARCH INSTITUTE FOR THE SEMI-ARID TROPICS

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Abstract

The very concept of sustainable intensification involves synthesis of two opposite forces. Intensification relates to the more intensive use of inputs to enhance the yields further. Sustainability looks at the longer term productivity of resources like land and water, which by its nature, applies brakes on the efforts to increase production by intensifying the use of inputs due to the fear that they may adversely impair the longer term productivity and resource quality/quantity. There may be a limited scope for increasing the use of inputs for realizing higher yields without impairing the longer term productivity of the critical resources. Sustainable intensification precisely looks at these limited opportunities. Over time, many researchers and institutions have used different contexts to define these terms. Very few researchers have attempted to systematically measure them on ground with selected cropping systems. The present study tried to use innovative approaches for generating profound evidences on sustainable intensification in semi-arid tropics of India with three dominant cropping systems located in Andhra Pradesh and Maharashtra states. The results are summarized in three case studies for better brevity of results and comparison.

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This work has been undertaken as part of the CGIAR Research Program on Policies, Institutions and Markets

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1. Introduction

Sustainable intensification is a term often used now in discussions around the future of agriculture and food security. The term actually dates back to the 1990s and was coined in the context of African agriculture, where yields are often very low, and environmental degradation is a major concern[1,2]. This pro-poor, smallholder oriented origin of the phrase is worth noting in the context of the current controversy around sustainable intensification.

Sustainable intensification (SI) has been defined as a form of production wherein *"yields are increased without adverse environmental impact and without the cultivation of more land"*[3]. In this sense, the term denotes an aspiration of what needs to be achieved, rather than a description of existing production systems, whether these are conventional high input-farming, or smallholder agriculture, or approaches based on organic methods. While the intensification of agriculture has long been the subject of analysis[4], sustainable intensification is a more recent concern (Garnett and Godfray 2012). It is still not clear what sustainable intensification might look like on the ground, how it might differ amongst production systems, in different places, and given different demand trajectories, and how the tradeoffs that inevitably arise, might be balanced. However it provides a framework for exploring what mix of approaches might work best based on the existing biophysical, social, cultural and economic context and a growing body of work is starting to emerge that explores what implementation might look like in practice[5].

Many researchers and institutions have used different contexts to define the term of 'sustainable intensification' in agriculture. At the same time, very few researchers have really attempted to conceptualize the sustainability framework and its measurement on ground with selected cropping systems. To fill this vacuum, the present study made an attempt to define these terms as well as measurement of those using suitable approaches. The broad perceptions of farmers about sustainable agriculture practices and the major drivers for adoption of such were also rarely captured and analyzed. The present study used a case study method to empirically measure the sustainable intensification practices on three prominent rainfed cropping systems in semi-arid tropics of India. A comprehensive set of sustainable intensification indicators were identified, estimated and compared among these three cases to deeply understand the issue of 'sustainable intensification' in the semi-arid tropics. On the whole, this synthesis report will be a one-stop source of information for measuring sustainable intensification of agricultural productivity in semi-arid tropics, India.

Comprehensively, the present study have covered three dominant rainfed cropping systems and their respective primary household surveys to intensely comprehend the issues of sustainable intensification. The brief details of those studies and their coverage are summarized below:

Case no	Name of cropping system	Reference year	Geography covered	Brief coverage details
First	Short-duration chickpea cropping system[6]	2011-12	United Andhra Pradesh	810 chickpea farmer households were interviewed from 30 mandals in seven districts
Second	Rainy season sorghum cropping system[7]	2012-13	Maharashtra	360 rainy season sorghum growing farmer households were covered from 20 mandals in 13 districts
Third	Pearl millet cropping system[8]	2012-13	Maharashtra	360 pearl millet cultivating farmer households selected from 20 mandals in nine districts

1. Reardon T, Crawford E, Kelley V and Diagana K (1996). Promoting Farm Investment for Sustainable Intensification of African Agriculture, Final Report, USAID
2. Pretty J (1997). The sustainable intensification of agriculture, Natural Resource Forum, Blackwell Publishing Ltd.
3. The Royal Society (2009). Reaping the benefits: Science and the sustainable intensification of global agriculture, London.
4. Boserup, E. 1965. The conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure. London: Allen & Unwin.
5. McDermott JJ, Staal S J, Freeman HA, Herrero M and Van de Steeg JA (2010). Sustaining intensification of smallholder livestock systems in the tropics, Livestock Science 130 (2010) 95-109.

Overall, the report has been organized into five sections. First section emphasizes about brief introduction, study focus and its coverage. The approaches for measuring agricultural intensification and sustainability are highlighted in section two. The empirical evidences from three case studies respective to three rainfed cropping systems are furnished in section three. Section four summarizes the feedback of farmer perceptions on sustainable agricultural practices and major drivers to adopt them. The study conclusions and way forward are provided in the last section of the report. The detailed analysis of crop simulations and econometric models are furnished in Appendices.

1.1 Definitions of Intensification and Sustainability

Intensification generally refers to the increased use of inputs. Growing more crops on the same land in a unit time period is referred as increasing cropping intensity. Increasing the use of manures, fertilizers, other chemicals like pesticides, fungicides and weedicides, human or bullock or machine labor, water etc, per unit area and time is characterized as the intensification of agriculture. The 'Green revolution' strategy banked on more and more intensive use of inputs to achieve higher yields. As the newly improved varieties and hybrids responded to the intensive-use of inputs by giving higher yields and economic returns, the process of agricultural intensification gained momentum in the irrigated regions of the country. In some areas, agricultural intensification caused environmental damage through increased salinity, alkalinity and water logging problems and limited the response to applied inputs. The policies of subsidization of fertilizers, water and electricity by governments have greatly aided the agricultural intensification process. Concerns about declining organic matter content, deficiencies of macro and micro nutrients and loss of balance between organic and inorganic manures and fertilizers and unbalanced use of nutrients have raised the issues of sustainability to the fore.

Scientists and environmentalists have emphasized the un-sustainability of the intensification process. The concern for sustainability of resources and long-term productivity of soil and water has resulted in new strategies of integrated nutrient management and integrated pest management practices. While these packages are developed by the research stations all over the country, they are not adopted by the farmers widely. Farmers are apprehensive of losing yield if they decrease the intensive-use of inputs. The non-governmental organizations have taken up the issues of pollution and environmental degradation caused by the intensive-use of inputs. They are promoting organic farming and, even natural farming as an alternative to intensive agriculture. But their reach is limited and the intensive-use of inputs is continuing unabated. However a certain degree of moderation is definitely setting in. The need of the hour is to strike a balance between high yields and sustainability. This urge has given rise to the concept of 'sustainable intensification'. Finally, it is always important to be clear on how it is defined. This concept aims to meet the multiple aspirations of society in terms of securing and increasing yields, as well as the benefits it values, such as protecting landscapes and wildlife. However, a common definition can be found below (Pretty et al. 2011):

Sustainable agricultural intensification is defined as producing more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services (Royal Society 2009; Godfray et al. 2010).

Russell (2005) identified differences in definitions predominantly related to the difference in an economist's and an ecologist's view of both intensification and sustainability. This seems to boil down to a short term view and a long term view of how to achieve sustainable intensification. Within the economic literature, agricultural intensification involves increasing the use of inputs per hectare, but also encapsulates bringing in previously uncultivated land into cultivation or increasing the use of fixed costs, such as labor, and machinery on cultivated land. In the view of Russell, this implies 'a short-run

6. For more details refer Bantilan et al. 2014

7. See also Kumara Charyulu et al. 2016a (forthcoming)

8. See also Kumara Charyulu et al. 2016b (forthcoming)

search for ways to increase variable inputs and output per hectare without comprising on the integrity of the ecosystem within which production is embedded'. He goes on to highlight a longer term view, adopted by natural science disciplines, that defines intensification as any increase in inputs per hectare plus any increase in output per hectare whether or not it is accompanied by an increase in inputs. Broadly speaking, therefore, we will define intensification as:

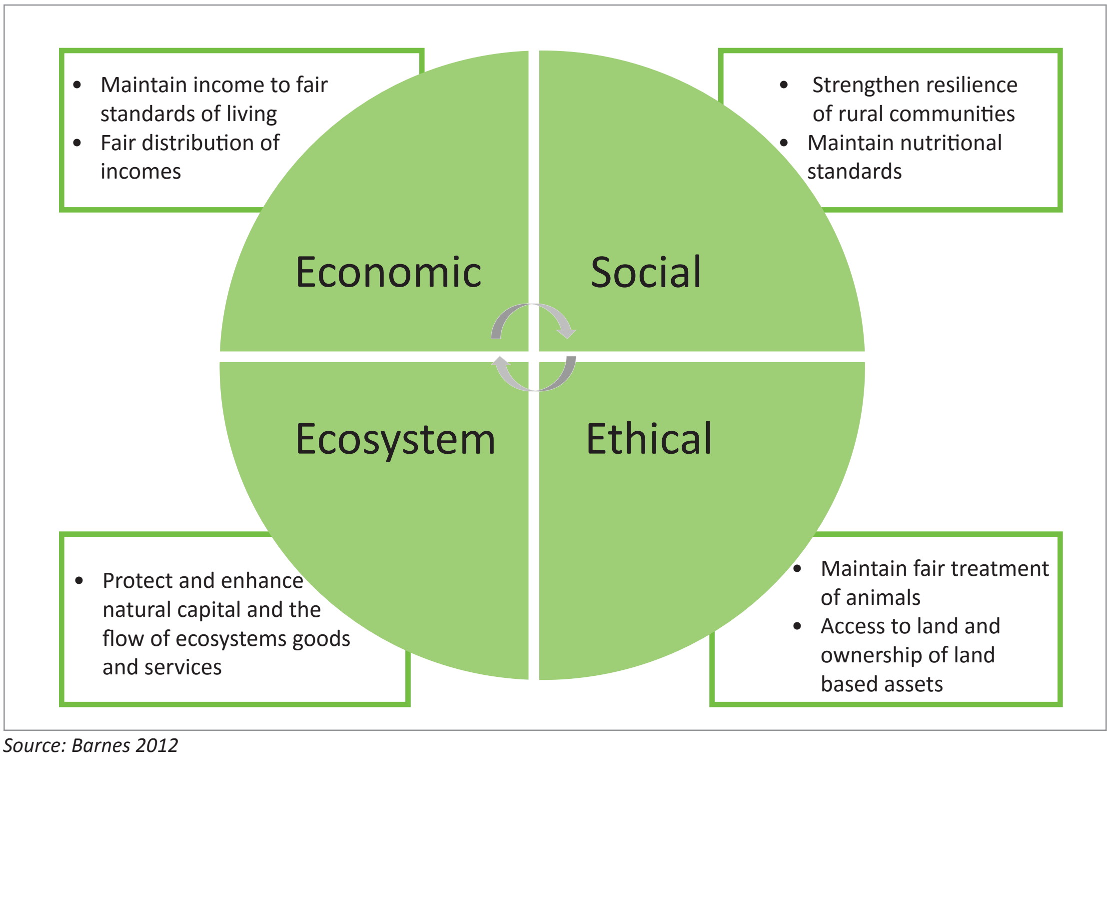
'….an increase in output per ha through technology and best practice adoption, as well as an increase in material inputs to increase output per ha' (Barnes 2012).

Overall sustainable intensification (SI) is a new, evolving concept, with its meaning and objectives subject to debate and contest. But SI is only part of what is needed to improve food system sustainability and is by no means synonymous with food security. Both sustainability and food security have multiple social and ethical, as well as environmental, dimensions. Achieving a sustainable, health-enhancing food system for all will require more than just changes in agricultural production, essential though these are. Equally radical agendas will need to be pursued to reduce resource-intensive consumption and waste and to improve governance, efficiency, and resilience.

1.2 Dimensions of Sustainable Intensification

Some thought is needed towards how sustainability could be defined. Sustainable intensification emerged from the ecological arena and, as such, policy and research documents seem to have a bias towards this area of sustainability. However, sustainability can cover a number of dimensions. With the current context of the study, sustainable intensification can be divided into four major dimensions which could be used as a basis for understanding sustainability within agricultural intensification.

In general, economic sustainability encompasses the income aspects of farming, covering both farmer and employer incomes, in terms of maintaining a sustainable level of income. This implies that the maintenance of a fair standard of living is indicated by economic factors. Net farm income will also have effects on the long-term sustainability of the system, through reducing debt ratios and by maintaining capital to ensure efficiency of operation.



Source: Barnes 2012

Social sustainability embeds the impact of farming within the rural communities under which it operates. Most studies are now finding a decoupling of farm income from rural communities (in terms of the input output impacts). In other words there is evidence of leakage of monetary payments.

Ecosystem sustainability and intensification is intrinsically linked with the biophysical capacity of primary inputs (MEA 2005). The most comprehensively studied aspects of intensification have been the relationship with other ecosystem services (Firbank et al. 2011; Storkey et al. 2011). This literature has generated a wealth of sustainable management recommendations, including initial explorations of sustainable intensification itself (Pretty 1995; Matson et al. 1997). Ethical dimensions of SI are also important and indeed these may not be included within a definition of sustainability.

2. Measuring Agricultural Intensification and Sustainability in semi-arid tropics

Semi-arid tropics have largely remained outside the process of excessive intensification, due to the paucity of water (Pingali 2012). Rather agricultural intensification was restricted to the smaller fractions of irrigated areas in the vast areas of the semi-arid tropics. In the rainfed areas, the response to applied inputs like fertilizer and plant protection chemicals was not profitable enough to motivate wider use of these inputs. The investments made in ground water exploration have often proved to be counter-productive and impoverished the farmers. Perhaps, the risk of failure has resulted in under-investment by the farmers to some extent (Rao et al. 2007). With the development of watershed management technologies and integrated nutrient and pest management strategies, there may be some scope for sustainable intensification. But, it may not be feasible as a general rule. The right crop combinations and rotations are required to further explore the scope of sustainable intensification in the semi-arid tropics (Srivastava et al. 1997; Pretty et al. 2014; Moeller, 2014). Detailed assessments of those systems are required to deeply understand the issue of where the scope still exists and where it has already reached its limit.

A workable definition is required to explore the range of complementarities between intensification and sustainability. Further, intensive-use of inputs should only be attempted if it does not compromise the long-term fertility and productivity of land and water resources in the semi-arid tropics. Wherever, intensive-use of inputs is already proving detrimental to the objective of long-term sustainability, either excessive input use has to be cut or the crop combinations/systems and rotations have to be modified. Of course, the requirements of human beings, livestock and other living beings should also be met in the short-run, while striving towards long-term sustainability. Technological change provides opportunities to push-up the production frontiers and increases the range of complementarities between intensification and sustainability. It is really the only hope to support the ever-growing populations of human beings and livestock. Wherever it fails to support them, people tend to migrate to more resource rich areas or urban conglomerations (Rao et al. 2007; Rao GDN et al. 2009). In some areas of semi-arid tropics, sustainable intensification is taking place while, in some other areas, people are migrating away as repeated droughts and famines are proving that the limits of sustainable intensification have already been reached.

Measuring sustainable intensification presents both conceptual and measurement difficulties. It is no small task to ensure that progress is being made towards increased sustainability, while also reconfiguring a farming system towards more intensive production. Measuring SI firstly requires appropriate monitoring. Whilst farm account surveys (FAS) provide indicators of input usage, they do not provide any spatial focus, or give an idea of the activity at the field or system level (Barnes 2012). Other data sets, such as national and census data could be merged with the FAS to provide a clearer picture on sustainable intensification. However, the intricacies of sustainable intensification could only be captured through detailed on-farm assessments over time, which, naturally, have cost associations for policy makers. Secondly, strong multi-disciplinary working is needed to set measurement goals. All the dimensions of sustainability should be fully captured within the measurement process. Furthermore, it is necessary to have a greater understanding of how to reconcile the (sometimes conflicting) indexes of sustainability and intensification which requires methodologies to extract weightings for individual indexes over different farming landscapes and, also, over time (Barnes 2012).

2.1 Approaches for Measuring Agricultural Intensification

The aim of this research is to examine and document the sustainable intensification process. This implies a temporal change, as opposed to simply examining intensity within one time period. Hence, datasets are needed to explore how it may have changed over time. A number of datasets are available that meet this criteria. In the present study context, both household primary survey data and secondary sources of information (area and production) reported by the Directorate of Economics and Statistics at the state-level was used for assessing agricultural intensification over time in particular geographical area units. To complement these sources of information, geospatial data which is available periodically for specific target locations was also used. The details of major approaches used in this study are summarized below:

2.1.1 Geospatial analysis for measuring intensity

Geospatial analysis is a modern innovative science tool for measuring agricultural intensification in a targeted location over a period of time. Both spatial and temporal changes in per unit cropped area will be captured with more precision and accuracy. This particular approach has been attempted initially in the case of chickpea crop in four districts (Anantapur, Kadapa, Kurnool and Prakasam) of Andhra Pradesh[9] and the process and results are highlighted below.

The Moderate-resolution imaging spectro-radiometer (MODIS) Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V005 (MOD13Q1 product) imagery was used for mapping chickpea area intensity over a period of time in Andhra Pradesh. The spatial resolution of the data is approximately 250 m. The data was adjusted for atmospheric correction (Vermote and Vermeulen 1999) and cloud screening. Each MODIS 16-day composite was further processed and cloud contamination was removed. The data were used to map spatial extent of land use/land cover focusing mainly on chickpea cropped area during 2000-01, 2005-06 and 2012-13. The monthly Normalized Difference Vegetation Index (NDVI) Maximum-Value Composition (MVC) were used for classification and an NDVI 16-day data set was used for identifying and labeling land use/land cover classes with chickpea areas.

Mapping land use /land cover and chickpea areas

The ideal spectra are generated using time series imagery for each ground truth point of same type of land use at spatially distributed location. The ideal spectra are the combination of the spectra of above locations representing a crop type class or crop dominance class. Land use/land cover class identification and labeling were based on MODIS NDVI time-series plots, ideal spectra, ground-truth data, and very high resolution images (Google Earth). The class spectra are matched with the ideal spectra and labeled with that class of land use. In rigorous classification process, most of the classes were identified and named. Ground data points collected from 449 locations during January, 2013 and 216 locations during October, 2005 were used to assess the accuracy of the classification results, based on a theoretical description (Jensen 1996; Congalton and Green 1999; Congalton and Green 2008) to generate an error matrix and accuracy measures for each land use/land cover map.

Chickpea expansion using NDVI signatures

A comparison was made between the land use changes areas and ideal spectra signatures (Figure 1) by using spectral matching techniques and ground data. In 2012 Chickpea areas were identified by taking into consideration the duration, magnitude, and peak of NDVI curve with ground data. A higher value of NDVI has been noticed during the rabi season (with the peak of NDVI observed during December/January) when compared with the kharif season.

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9. Refer Murali Krishna Gumma et al. (2016)

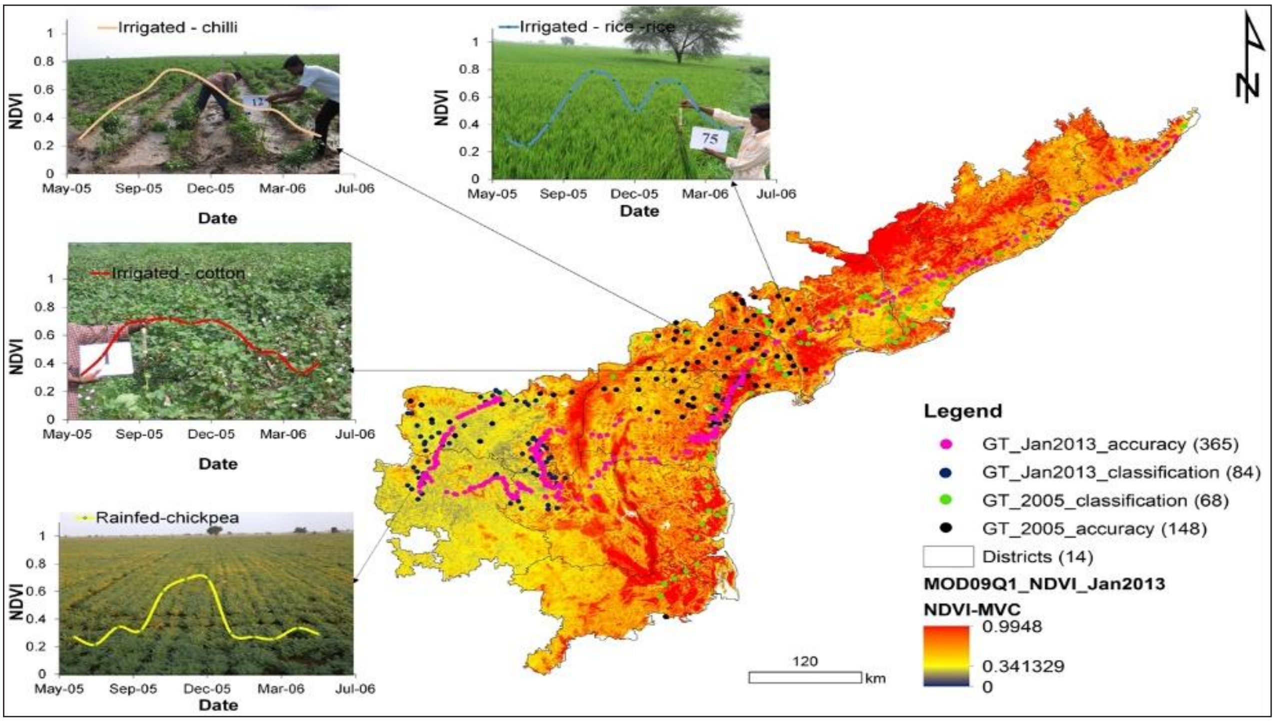

Figure 1. Ground data point locations for chickpea in Andhra Pradesh.

2.1.2 Primary and secondary sources of data

In the present study, both primary and secondary sources of information were complemented to understand the intensification process over a period of time in the targeted states. Specifically, three nationally representative household surveys[10] were conducted by International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) for each study region and crop. Further, the details of each survey were briefly explained in the respective case studies. Secondary information on both crop area and production were also obtained from the respective 'State Directorate of Economics and Statistics' over the last three decades to deeply understand the intensification process. The results of this data are presented and discussed in section 3.

2.2 Approaches for Measuring Agricultural Sustainability

Sustainable agriculture implies long-term maintenance of natural systems, optimal production with minimum input, adequate income per farming unit, fulfillment of basic food needs, and provision for the demands and necessities of rural families and communities (Brown et al. 1987; Liverman et al. 1988; Lynam and Herdt 1989). All definitions of sustainable agriculture promote environmental, economic and social harmony in an effort to capture the meaning of sustainability. Sustainability being a concept, it cannot be measured directly. Appropriate indicators must be selected to determine the level and duration of sustainability (Zinck and Farshad 1995). An indicator of sustainability is a variable that allows us to describe and monitor processes, states and tendencies of the agricultural production systems at various hierarchical scales, including the cropping, farm, regional, national and worldwide levels.

The present study basically dealt with two approaches for addressing the issue of sustainability at the farming system level rather than at the firm unit level. Since sustainability is a long-term phenomenon, it cannot be judged either at a single point of time or at a single firm unit. Due to limitations in the data sources, an integrated approach was followed using both long-term crop simulation models as well as primary household survey data to assess various indicators of sustainability. The details of those approaches are summarized and discussed below:

10. See Bantilan et al. (2014) for chickpea; see Kumara Charyulu et al. (2016 a&b) for sorghum and pearl millet respectively.

2.2.1 Crop simulation models

Crop simulation models are valuable tools for assessing sustainability of cropping systems. Some of the methodological challenges in assessing sustainability both temporarily and spatially can be addressed using crop simulation models. Hence we used a crop simulation model-based sustainability assessment in a fallow-chickpea, fallow-maize and fallow-sorghum based cropping systems based cropping system in semi-arid regions of Andhra Pradesh, India using the CROPGRO-Chickpea, CERES-maize and sorghum models. Similarly in Maharashtra we studied sorghum-chickpea, soybean-chickpea and sorghum-fallow systems. The chickpea model part of the suite of crop models available in DSSAT v4.5 software (Hoogenboom et al. 2010). The major components of the model are vegetative and reproductive development, carbon balance, water balance and nitrogen balance. It simulates crop growth and development using a daily time step from sowing to maturity and ultimately predicts yield. Genotypic differences in growth, development and yield of crop cultivars are affected through genetic coefficients (cultivar-specific parameters) that are inputs to the model. The physiological processes that are 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.

Model inputs

The minimum data sets required to simulate a crop for a site include site location and soil characteristics, daily weather and agronomic management data. The model also needs input of cultivar-specific parameters (genetic coefficients) that distinguish one cultivar from another in terms of crop phenology, growth and partitioning to vegetative and reproductive organs and seed quality. The soil-profile data for the study sites were obtained from the profile characteristics data published by ANGR Agricultural University, Hyderabad and NBSSLUP, Nagpur.

Weather data

Thirty-years (1980-2010) of observed daily weather series was obtained from ANGR Agricultural University, the Agromet observatories located at Anantapur, Nandyal, IMD observatories in Ongole and from the NASA AgMERRA data sets. Similar datasets were also obtained from the Agromet Divisions of MAU, Parbhani for sorghum crop simulations as the representative location for the Marathwada region. Simulation studies were not attempted in other regions of Maharashtra due to non-availability of soil and long-term weather datasets. Crop simulations studies were not attempted in case of pearl millet due to the lack of a well calibrated pearl millet model. The baseline weather datasets were quality controlled and inspected for outliers or anomalous values and if found, such values were adjusted and corrected using bias corrected AgMERRA data. AgMERRA consists of historical climate datasets prepared based upon a combination of daily outputs from retrospective analyses (reanalyses), gridded temperature and precipitation station observations, and satellite information for solar radiation and rainfall (Ruane et al. 2014).

Model-based sustainability assessment

To develop a model-based sustainability assessment, the present study selected four chickpea growing districts having different soil and weather conditions and are representative of each of the four major districts. We initially reviewed key issues for agricultural sustainability and key cropping system followed in these districts prior to chickpea adoption. We also surveyed the current chickpea management practices followed in each of the districts by the farmers and then reviewed the improved management strategies and decided to include farm yard manure application, supplemental irrigation and advancing sowing dates in simulated fallow-chickpea rotations. In the present study we evaluated eight sustainability indicators, crop yield, water-use efficiency (WUE), the amounts of soil total organic carbon (OC) across cycles of the rotation, nitrogen fixing, nitrogen leaching, nitrogen-use-efficiency, inorganic nitrogen in soil at maturity and total nitrogen uptake at maturity. We later explored the simulation scenarios of the various crop rotations, management options and used sustainability polygons to illustrate the sustainability state of chickpea rotations compared to traditional fallow-sorghum/maize rotations. Similarly, dominant sorghum and soybean systems/pear millet and maize systems existing at the locations in Maharashtra were also tested and evaluated for sustainability issues.

2.2.2 Econometric analysis

There are a number of frameworks available for assessing sustainability that evaluate performance at the macro and micro levels and there is now rapidly developing literature on the use of sustainable indicators. Approaches commonly known by researchers in evaluating sustainability include either studying individual components or integration of all four major components of sustainability i e, ecological, economic, social and ethical. In the present study, to measure sustainability, household survey data collected from designated studies was used to derive indicators of economic sustainability. A range of sustainability indicators[11] were generated from the survey relating to ecological, economic and social dimensions. One of the main purposes of present study was to elicit changes across the farming systems and agro-ecological regions and derive conclusions about sustainability across study locations.

Sustainability was measured by integrating all the major components except the policy as this is beyond the scope of the data collected and of the present study. To analyze the sustainability among different systems, initially simple statistical means were used following which econometric methods (such as Cobb-Douglas and Stochastic Frontier production functions) were applied. While assessing the efficiency of different resource-uses in diverse production systems, robust techniques (such as PCA) and variables were used to integrate the economic, social and ecological dimensions of sustainability at the household level.

The following indicators were identified and analyzed across study regions to compare the sustainability indicators for an alternative management system relative to values obtained with a reference system using sustainable polygons (ten Brink et al. 1991). The present study used the long-term average values for all the indicators studied such as yield per ha, water-use efficiency (WUE), nitrogen-use efficiency (NUE), total organic carbon at maturity (OCTAM), nitrogen by phosphorus (N/P) ratio, returns over variable costs (ROVC), fodder availability per acre (FAA), share of ROVC in total expenditure and share of cereal consumption to total food production.

The parameter yield per ha was used mainly because it integrates all factors of crop production and measures the efficiency with which all the resources and inputs converted in to single physical output. Water-use efficiency (WUE) is the efficiency with which the highly scarce and variable rainfall is converted into yield. Nitrogen-use efficiency (NUE) is a measure of efficiency with which the highly dynamic nitrogen

Parameter	References
1. Parameters estimated through crop simulation models	
1.1 Crop yield	Hayati et al. 2010; Moeller et al. 2014
1.2 Water-use efficiency (WUE)	Moeller et al. 2014
1.3 Nitrogen-use efficiency (NUE)	Hayati et al. 2010; Moeller et al. 2014; Murray-Prior et al. 2005
1.4 Total organic carbon at maturity (OCTAM)	Moeller et al. 2014; Arshad and Martin 2002;
2. Parameters estimated through primary household data	
2.1 Return over variable cost (ROVC)	Rasul and Thapa 2003; Moeller et al. 2014
2.2 Fodder availability per acre	-
2.3 Share of ROVC in total household food expenditure (%)	-
2.4 N/P ratio	Rasul and Thapa 2003
2.5 Share of household cereal consumption in total food production (%)	Hayati et al. 2010

11. See appendix-1 for more details

input is converted into yield. The total organic carbon is a key indicator for soil health and it integrates important soil properties such as aggregate soil stability, nutrient availability and water retention (Moeller et al. 2014).

Return over variable costs (ROVC) measure the degree to which a system is economically viable in short-run. Livestock is an integral component of semi-arid tropics agriculture. It contributes significant share of farmer annual household income (Rao et al. 2007). Hence, production of fodder per unit area per household is a key sustainable determinant. The share of ROVC in the total household food expenditure shows the economic sustenance of an average household. NPK ratio of 4:2:1 ($N:P_2O_5:K_2O$) is generally considered ideal and accepted as best agricultural nutrient management practice. However, in the present study we have used N/P ratio as a measure for assessing the sustainable usage of fertilizer application across different cropping systems in a specified targeted location. The average household food production as a proportion of cereal consumption indicates the extent of food security of household members.

Cobb-Douglas production function

The present study applied the Cobb-Douglas production function to assess the production efficiency of various crop inputs across major cropping systems in the study region. Nine explanatory variables were identified to explain efficiency of various inputs used in the system. As the units differ from one explanatory variable to other, we harmonized them by multiplying with costs obtained while conducting the field survey. The following form of The Cobb-Douglas production function was fitted for the analysis:

$\text{Log } Y_i = \log a + b_1 \log X_1 i + b_2 \log X_2 i + b_3 \log X_3 i + b_4 \log X_4 i + b_5 \log X_5 i + \log \mu_i$

Where,

Y_i : Gross revenue per ha

'a': Constant parameter in the equation, and 'X_{1-n}' are defined as below and vary according to the cropping system.

Cropped area (in ha), labor cost per ha, bullock cost per ha, manure cost per ha, machinery cost per ha, irrigation cost per ha, seed cost per ha, fertilizer cost per ha and plant protection cost per ha were used as explanatory variables in assessing resource-efficiency.

Returns to scale:

Returns to scale is the measure that defines how much additional output will be obtained when all factors change proportionally.

Returns to scale = Σb_i

If returns to scale =1, the production function has constant returns to scale.

If returns to scale > 1, the production function has increasing returns to scale.

If returns to scale < 1, the production function has decreasing returns to scale.

Stochastic frontier production function

Any cropping system is sustainable if the productivity is not stagnating or declining. Stagnating/declining yields are indicative of this serious concern (Pingali and Heisey 1999). Consequently, future gains in productivity also depend on improving the utilization efficiency of the agricultural resource base particularly land. This requires greater access to information and an improvement in the management potential of farmers (Rejesus et al. 1999).

Following Aigner et al. 1977 and Kumbhakar et al. 2000, relative efficiency of farmers was analyzed to have a basic understanding of sustainability using the stochastic frontier production function which was given as below:

$$TE_i = \frac{y_i}{(\chi_i\, ;\, \beta).\exp\{V_i\}}$$

Where,

TE refers to the technical efficiency of the i[th] farm, y_i is the observed output, f (X_i ; β) indicates the deterministic part that is common to all producers, exp {V_i} is a producer specific part, which captures the effect of random noise on each producer.

According to Battese and Coelli (1995), technical inefficiency effects are defined by:

$U_i = Z_{i\delta} + w_i$

Z_i is a vector of explanatory variables associated with the technical inefficiency effects, δ is a vector of unknown parameters to be estimated, and w_i represents unobservable random variables, which are assumed to be identically distributed. They are obtained by truncation of the normal distribution with mean, zero and unknown variance σ^2, such that U_i is non-negative.

All crop outputs and inputs were converted into monetary values using the price information collected during the survey (Bamlaku et al. 2009). The model specified was given here:

LnY = β0 + β1*ln* Area + β2*ln* Land cost *+* β3*ln* Bullock cost + β4*ln* Machinery cost + β5*ln* Seed cost + β6*ln* Manure cost + β7*ln* Fertilizer cost + β8*ln* Pesticide cost + δ1Age + δ2 District1+ δ3 District2 + δ4 Distric3 + δ5 Education +δ6 Crop diversification index+ δ7 Network index + ε

Principal Components Analysis (PCA)

Principal components analysis (PCA) is a technique for determining the key variables in a multi-dimensional data set that explain the differences in the observations. This is a method of data reduction and provides a way of weighting all the variables related to the underlying structure of the data. The PCA approach provides a relatively simple means of exploring the issue of weighting different dimensions of sustainability and intensification. The coefficients derived from this analysis were mapped to find the way forward and to assess the impact of the integrated components on sustainability.

The main problem of aggregation of parameter values is that they may be expressed in different units (Gomez-Limon and Riesgo 2008). So normalization of parameters is important. In this study the normalization technique by Freudenberg (2003), re-scaling in a range [0, 1] was adopted. In this sense, after normalization, the scores of indicators range between 0 (the worst value, meaning the least sustainable option) and 1(the best value, corresponding with the most sustainable option). Equation 1 & 2 were used for normalization among various inputs.

$$I_{ki} = \frac{x_{ik} - Min\ x_{ik}}{Max\ x_{ik} - Min\ x_{ik}} \ldots\ldots\ldots.(1)$$

$$I_{ki} = \frac{Min\ x_{ki} - x_{ki}}{Max\ x_{ki} - Min\ x_{ki}} \ldots\ldots\ldots..(2)$$

Nine indicators derived from respective household surveys data were chosen for the PCA analysis and they are: return over variable cost (ROVC), n/p ratio (NP), fodder availability per acre, share of ROVC in total household food expenditure, crop diversification index, network index, age and education level etc. Indices like network, age of household and level of education represents the social components of sustainability.

The present study did not attempt to develop any composite indicator to assess the sustainability across systems due to limitations in the household data. However, the study made a systematic effort to analyze the available cross-sectional household data to address the issue of agricultural intensification and sustainability. Indicative sets of evidence on agricultural intensification and sustainability were documented in semi-arid tropics, India. However, more robust and concrete evidence could be generated through long-term panel studies and datasets.

Overall, the following summary of approaches and key indicators were used to assess the intensification and sustainability of different cropping systems in study locations and crops.

Approach	Key indicator	What is measured	How it is measured
Geospatial analysis	Intensification	MODIS NDVI values over time	Land use change with ground trothing
Primary data	Intensification	Simpson index/crop diversification index	Share of crop area in total HH landholding
Secondary data	Intensification	% share in net sown area over time	Share of crop area in total state net sown area
Crop simulation models	Sustainability	Crop yield per ha	
		Water-use efficiency (WUE)	
		Total organic carbon at maturity (OCTAM)	
		Nitrogen-use efficiency (NUE)	
		Nitrogen fixed during crop season (NFXM)	
		Nitrogen leached during crop season (NLCM)	
		Inorganic nitrogen at maturity (NIAM)	
		uptake (CNAM)	30 years of crop simulated data
Econometric models	Sustainability	Returns to scale	Cobb-Douglas production function
		Technical efficiency of inputs	Stochastic frontier production function
		Drivers of sustainability	Principal Components Analysis

3. Evidence for Agricultural Intensification and Sustainability

To document possible evidence from the semi-arid tropics of India, the present study has taken three specific cases purposefully to assess the agricultural intensification and sustainability of existing cropping systems in the three targeted states. Correspondingly, three comprehensive and representative household surveys were carried out with structured survey instruments. The data was validated, analyzed and is presented below as three case studies. The results were also complemented with both geospatial analysis and long-term crop simulation models.

Case 1: Chickpea cultivation in Andhra Pradesh

Chickpea cropping system was selected as a first case to deeply understand the agricultural intensification and sustainability aspects from Andhra Pradesh. In recent times, the chickpea crop in the state has expanded significantly (ten folds) and shown a remarkable increase in crop productivity (doubled) during the last two decades period due to development and introduction of short-duration chickpea cultivars which are resistant to Fusarium wilt disease. The extent of adoption of those cultivars reached its peak within a span of eight years because of strong institutional support (Department of Agriculture), seed supply (APSSDC) and a conducive policy (hike in minimum support price) environment[12]. Due to the high market demand and the suitability of chickpea for mechanical cultivation, the unit rental values of land have gone-up significantly in the major study districts. Because of these peculiarities, this would be a classical first case for understanding the intensification and sustainability issues in semi-arid tropics.

[12]. For more details refer Bantilan et al. 2014

3.1.1 Geospatial analysis of chickpea

This study produced crop extent maps for Andhra Pradesh including other land use / land cover areas at 250 m spatial resolution using MODIS imagery and ground data. These maps were tested for accuracy using ground data collected by this research team and national statistical data obtained from government agencies. Temporal variation on chickpea areas in Andhra Pradesh from 2000-01 to 2005-06 and 2012-13 at the district level are shown in the table below and, spatial maps are shown in Figure 2.

Figure 2 also provides spatial information for chickpea and shows the expansion in chickpea cultivation in the major chickpea-growing districts. In Figure 2a, the total chickpea area mapped was 168,362 ha in these four districts and this was located in rainfed-black cotton soils. In Figure 2b, total chickpea area was increased to 389,361 ha in these four districts and finally Figure 2c the area mapped was 558,713 ha. Anantapur and Prakasam districts were largely expanded in their chickpea cultivation when comparing from 2005-06 to 2012-13: more than 65% increase in chickpea area under plantation. Overall four districts together, the chickpea area of 2012-13 was increased by 232% compared from 2000-01.

Major expansion chickpea areas across Andhra Pradesh derived from MODIS 250 m.

	Area (ha)		
Districts	Year-2000	Year-2005	Year-2012
Anantapur	34777	51304	84493
Kadapa	30343	69258	117903
Kurnool	68113	140511	196793
Prakasam	35129	128288	159524

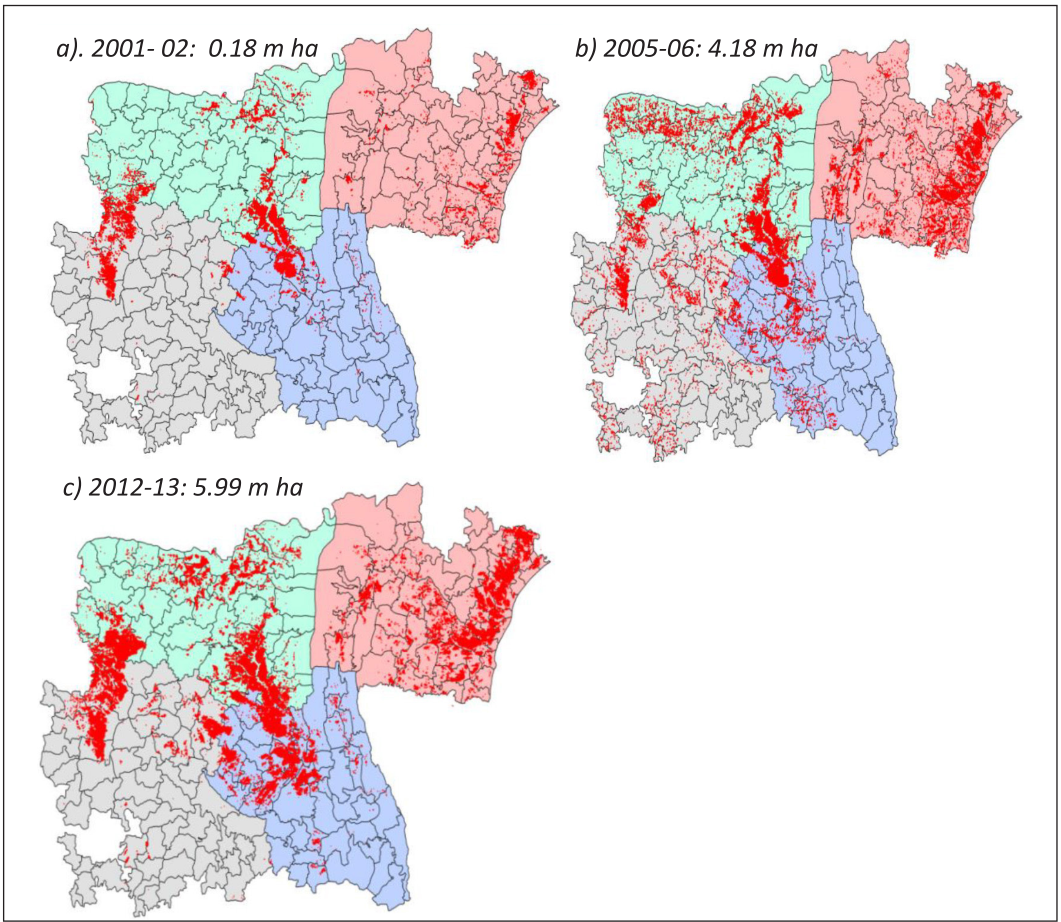

Figure 2. Geospatial analysis of chickpea expansion in Andhra Pradesh.

3.1.2 Primary and secondary data analysis

As discussed earlier, both primary and secondary data was used to assess the chickpea crop intensification of agriculture in Andhra Pradesh. The details of primary household survey, sampling framework and its coverage etc. were summarized in Appendix-2 (also see Bantilan et al. 2014).

Figure 3 illustrates the share of chickpea area in the total net sown area of the state between 1996 and 2010. Until the early 1990s, the share of chickpea in the state was confined to below 0.010. After that it showed a remarkable increase and reached its peak by 2009 (0.060). Later it declined slightly and reached 0.050. This clearly reveals the intensification of chickpea in the state during the last two decades.

In order to understand the relative importance of chickpea in the cropping pattern of the selected chickpea growing districts, triennial averages of chickpea area to the total net sown area are worked out and are presented for three different time periods, 1990-92, 1999-2001 and 2007-09 in Table 1. It can be seen that the share of chickpea in total sown area has gone up 31 times in Prakasam district during the 17 year period, 1990-92 and 2007-09. The same increased by 11 times in the case of Kurnool district, by nearly 10 times in Kadapa district and by nearly 12 times in the case of Anantapur district. In the same way, the share of chickpea in total sown area went up 15 times in Mahabubnagar district, by 10 times in Nizamabad district and by three times in Medak district. Thus, in all the seven major chickpea growing districts of Andhra Pradesh, the share of chickpea increased several fold, although the degree of increase differed in each case. Prakasam district recorded a phenomenal growth of 31 times, while growth was modest at three times in the case of Medak district at the other extreme.

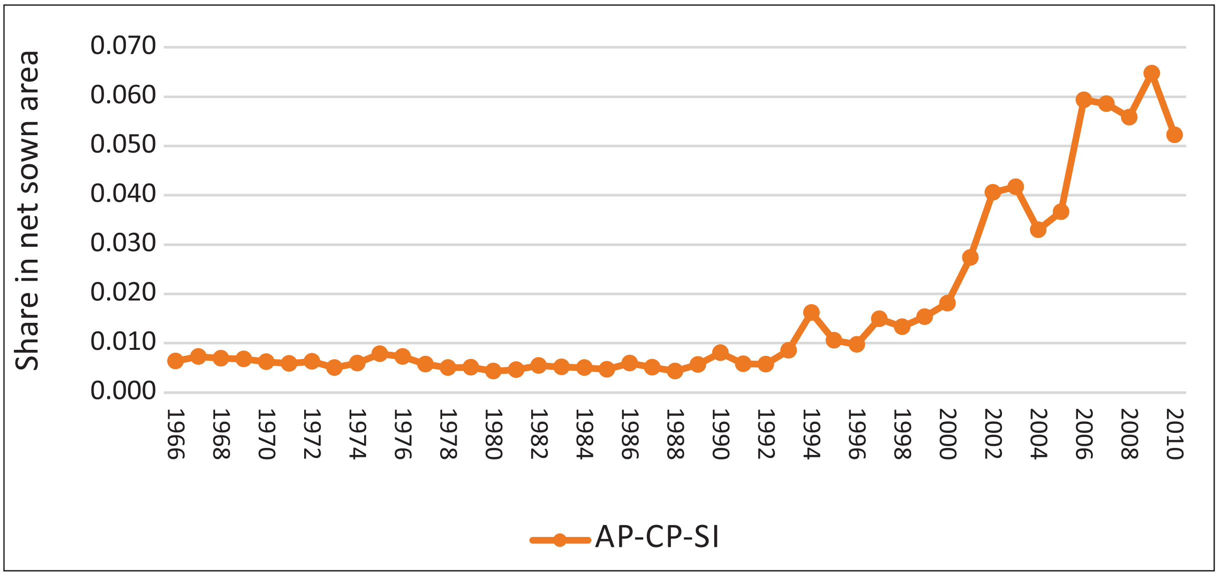

Figure 3. Share of chickpea in net sown area in Andhra Pradesh.

Table 1. Share of chickpea in net sown area of selected districts in Andhra Pradesh.

Triennium	Prakasam	Kurnool	Kadapa	Anantapur	Medak	Nizamabad	Mahabubnagar
1990-92	0.005	0.024	0.012	0.007	0.029	0.010	0.002
1999-01	0.056	0.092	0.082	0.035	0.043	0.009	0.006
2007-09	0.156	0.264	0.115	0.082	0.090	0.101	0.030

In the case of primary sample household survey farmers (N=810) also, the area allocated to chickpea by them showed an increase. The Simpson index computed clearly indicated an increased allocation of land by the farmers to chickpea (Figure 4). The scatter diagram showed that the intensification ranged between 0.80 and 1.00 for different sample farmers.

The measure of intensification indicated that it was highest in the case of small farmers. For the large and medium categories of farmers, the measure of intensification averaged 0.70, while it touched 1.00 in the case of small farmers, indicating complete specialization in chickpea (Figure 5).

3.1.3 Assessing chickpea sustainability using crop simulation models

The geospatial and secondary data together revealed that the cropped area under chickpea has increased nearly ten folds and intensified in the state during the last two decades (1990-2010). At this stage, it is worthwhile to assess the sustainability of chickpea cultivation in the state. The present study used the well calibrated and evaluated CROPGRO-chickpea model (Singh et al. 2014a) using the JG 11 cultivar to document long-term indicators for sustainability in fallow-chickpea vs fallow-maize/sorghum systems in study locations.

Using a crop-simulation model, different efficiency parameters were computed for the three major cropping systems (fallow-chickpea, fallow-fallow and fallow-maize/sorghum) using improved management practices (*under ideal situations*) and they are reported in Appendix-2 Tables A5, A6, A7 and A8 respectively for the districts of Prakasam, Kurnool, Kadapa and Anantapur. The improved package of practices include early sowing, recommended fertilizer application and integration of organics, providing, providing supplemental irrigation at 60 DAS and maintaining of optimum plant population.

We used the long-term average values of the sustainability indicators for an alternative management system such as fallow-sorghum/maize relative to the values obtained with reference system (fallow-chickpea) using sustainability polygons. In case of all the four districts, fallow-chickpea gave the best yields (in terms of chickpea equivalent yield) when compared with the fallow-maize/sorghum system. It also scored better in terms of water-use-efficiency and nitrogen-use-efficiency. Chickpea system outperformed the other two systems in terms of other parameters such as nitrogen fixed during the crop season, inorganic nitrogen uptake at maturity and crop nitrogen. Thus, the fallow-chickpea system stood out as the best system in the four study districts. No wonder, chickpea was able to perform best both in terms of productivity as well as sustainability indicators. These positive factors might have contributed to the crop intensification in the state. It is, indeed, a case of sustainable intensification.

The fallow-chickpea system reported a nearly 92% higher yield than the chickpea equivalent yield given by the fallow-maize system in Prakasam district. Besides reporting a higher yield, it also scored better with

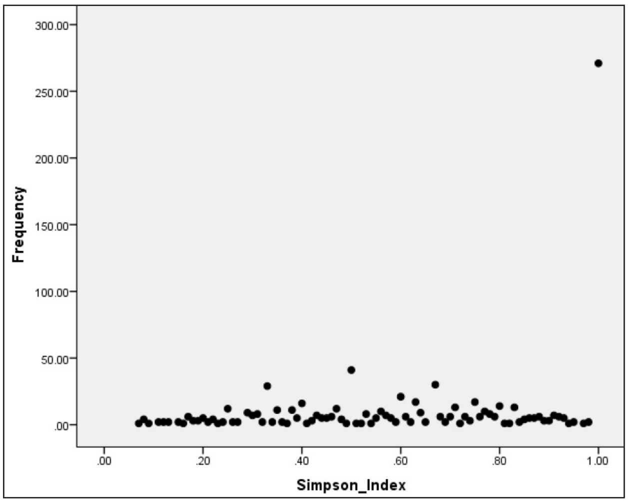

Figure 4. Intensification of chickpea among sample farmers (n=810).

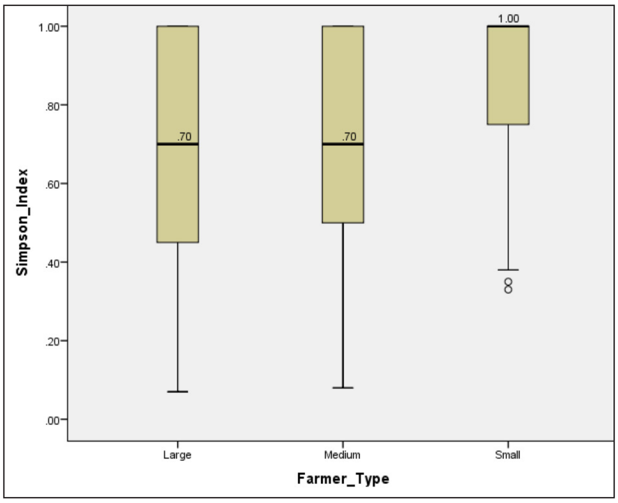

Figure 5. Intensification of chickpea by category of farmers.

other indicators of sustainability (see Appendix-2 Table A5). The water-use-efficiency was more than twice that in case of fallow-maize system. Being a leguminous crop, chickpea reported nitrogen-use-efficiency which was higher than that of the competing system by hundreds of times. This was also the case with the nitrogen availability at crop maturity.

The yield advantage with fallow-chickpea is much higher when compared with the chickpea equivalent yield of fallow-sorghum system in Kurnool district (see Appendix-2 Table A6). The fallow-chickpea system gave a 267% higher yield than the fallow-sorghum system. The water-use-efficiency of both these systems was almost the same. But, the fallow-chickpea system scored far better with respect to nitrogen-use-efficiency, total nitrogen level at crop maturity and the nitrogen-phosphorus ratio.

Just as in the case of Kurnool district, the fallow-chickpea system in Kadapa district out yielded the fallow-sorghum system (equivalent yield to chickpea) by 283% (see Appendix-2 Table A7). The water-use-efficiency was also higher in the fallow-chickpea system, unlike the case in Kurnool district. Being a leguminous crop, chickpea recorded far higher levels of nitrogen-use-efficiency and total nitrogen availability at the harvest. Similarly, nitrogen fixation during the crop season and total organic carbon accumulation in the soil was far better in the case of fallow-chickpea system than in the fallow-sorghum system.

The results of analysis of productivity and sustainability indicators for the Anantapur sample were also on the same lines as that of Kadapa district (see Appendix-2 Table A8). The productivity of the fallow-chickpea system was 139% higher than that of the fallow-sorghum system when its equivalent yield to chickpea was considered. The water-use-efficiency was also higher with the fallow-chickpea system. Naturally, the leguminous crop chickpea recorded far higher nitrogen-use-efficiency as well as nitrogen level at crop maturity.

Chickpea yields (average of 30 years) were compared with the historical sorghum/maize yields across study districts and summarized in Figure 6. In Prakasam district, chickpea yields were about twice those of maize. In the other three districts, chickpea yields were more than twice that of sorghum yield in the postrainy season.

The simulation results indicate that the chickpea yields are much higher with the improved practices (IMP) than with the farmers' practice (FP) in all the four major chickpea growing districts of Prakasam, Kurnool, Kadapa and Anantapur (Table 2). The other efficiency parameters such as water-use-efficiency (WUE), nitrogen-use-efficiency (NUE), nitrogen fixed during the crop season (NFXM) and organic carbon at maturity (OCTAM) were also higher when improved practices were followed. The nitrogen leached during the crop season (NLCM) and inorganic nitrogen at maturity (NIAM) was lower with the improved practices when compared with those under farmers' practice. The total crop nitrogen (CNAM) was higher with the improved practices than with farmers' practice in all the districts except Kurnool.

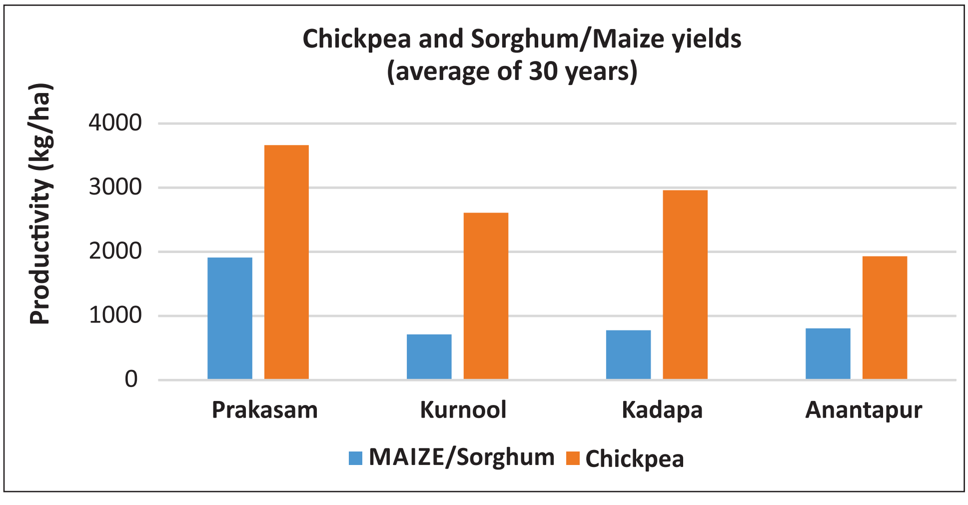

Figure 6. Mean equivalent yields of chickpea and competing crops.

Farmers were found to be using more nitrogen per hectare (39 to 98 kg per ha) and higher seed rates (103 to 123 kg per ha). They were also maintaining a larger plant population per sq. meter (40 to 45). They were sowing chickpea between September and November (Table 3).

Improved practices were found to be the best as they emphasized balanced fertilizer application along with organic fertilizers which are environmentally sustainable practices (Table 4). The seed rates were lower than in the case of farmers' practices by about 30-40%. This involves considerable saving in seed cost and wider spacing. Consequently, the plant population per square meter was lower by 25-30% in case of the improved practices.

Table 2. Sustainability of chickpea cultivation in study districts.

	Prakasam		Kurnool		Kadapa		Anantapur	
Parameters	FP	IMP	FP	IMP	FP	IMP	FP	IMP
Yield	2666	3662	2582	2609	2045	2961	1133	1927
WUE	5.94	7.42	5.86	5.92	5.01	6.28	2.95	4.28
NUE	27.21	183.12	40.36	130.50	52.44	148.05	28.33	96.38
NFXM	47.17	136.37	60.50	91.70	40.80	79.30	31.33	66.17
NLCM	51.07	46.87	9.07	7.73	13.70	10.13	11.77	8.67
NIAM	180.70	85.47	144.20	111.13	185.13	113.80	130.97	62.27
CNAM	133.93	168.50	129.93	127.93	111.23	144.30	82.07	111.43
OCTAM	127.14	132.70	128.15	134.25	127.99	134.11	112.04	118.27

Yield: kg/ha; WUE: Water use efficiency (kg/ha mm); NUE: Nitrogen use efficiency kg grain/kg N applied; NFXM: Nitrogen fixed during crop season (kg/ha); NLCM: Nitrogen leached during crop season (kg/ha); NIAM: Inorganic nitrogen at maturity (kg/ha); CNAM: Crop nitrogen uptake (kg/ha) and OCTAM: Total organic carbon at maturity stage (tons/ha)

FP: Farmers' practice; IMP: Improved management practice

Table 3. Farmers' practices in chickpea cultivation across study districts.

Parameter	Anantapur	Kadapa	Kurnool	Prakasam
FYM (ton/ha)	-	-	-	-
Total 'N' per ha	40	39	64	98
Seed rate per ha	106	103	105	123
Plant Population per sq m	40	40	40	45
Sowing window	9/15 to 10/15	10/5 to 11/5	9/15 to 10/15	11/5 to 11/25
Irrigation	-	-	-	-

Source: Field survey

Table 4. Improved chickpea management practices across study districts.

Parameter	Anantapur	Kadapa	Kurnool	Prakasam
FYM (ton/ha)	5	5	5	5
Total 'N' per ha	20	20	20	20
Seed rate per ha	75-80	75-80	75-80	75-80
Plant Population per Sq m	30-35	30-35	30-35	30-35
Sowing window	9/16 to 9/30	10/1 to 10/15	9/16 to 9/30	10/15 to 11/1
Irrigation (mm)	50	50	50	50

Source: Improved practices, ANGRAU

3.1.4 Simulated soil carbon dynamics of chickpea system over last thirty seasons

The carbon sequestration was better with improved practices of fallow-chickpea (F-C-RP) when compared with the farmers' practice of fallow-chickpea (F-C-FP) (see Appendix-2 Figure A2). Even the fallow-sorghum (F-S) system resulted in better carbon sequestration than the fallow-fallow (F-F) system. The model simulation results from the Anantapur revealed that the improved practices of the fallow-chickpea system yielded higher carbon sequestration than fallow-sorghum and fallow-chickpea under farmers' practices. All these three systems gave better results than the fallow-fallow system.

The simulation results for for Prakasam district also gave similar results as in case of Anantapur district (see Appendix-2 Figure A3). The fallow-chickpea system with improved practices gave the best carbon sequestration among the four systems under comparison. The fallow-sorghum system and fallow-chickpea system with farmers' practices had almost similar patterns of carbon sequestration. The fallow-fallow system was the least efficient of all in carbon sequestration.

The model simulation results for Kurnool district followed the same ranking as in Anantapur district (see Appendix-2 Figure A4). The fallow-chickpea was the best one, followed by fallow-sorghum and fallow-chickpea with farmers' practices. The fallow-fallow system was the least efficient of all the four in carbon sequestration.

The simulation results for Kadapa district were also similar to those of Anantapur and Kurnool districts (see Appendix-2 Figure A5). As in the case of the other districts, fallow-chickpea with improved practices proved to be the best and it was followed by fallow-sorghum and fallow-chickpea with farmers' practices. The fallow-fallow system was least effective in carbon sequestration.

3.1.5. Assessment of chickpea economic sustainability

The economic sustainability was assessed based on primary data collected during the household surveys. The returns over the variable cost (ROVC) per ha for fallow-chickpea estimated were higher by 21% than those for the fallow-maize system (Table 5). But, fallow-maize supplied approximately six times higher chickpea equivalent fodder per acre than the fallow-chickpea system. Both the systems had similar shares of returns over variable costs in the total household expenditures, indicating the comparable income security of the crops. While the fallow-maize system used 2.7 times higher nitrogen relative to phosphorus, chickpea used less than one half of nitrogen as compared to phosphorus. Both the systems were at par with respect to cereal consumption as a share of food production.

The returns over variable costs were also comparable for both these systems in Kurnool district (Table 5). Chickpea equivalent fodder availability per acre was significantly higher for the fallow-sorghum system than for the fallow-chickpea system. Similarly, the fallow-sorghum system recorded a marginally higher share of returns over variable costs as a proportion of total household expenditure. But, the N/P ratio was estimated to be much higher in the fallow-sorghum system than in the fallow-chickpea system. Both the systems appeared to be similar with respect to share of cereal consumption in total food production. Thus, the fallow-chickpea system stood out both with respect to productivity as well as efficient utilization of resources.

The fallow-chickpea system gave much higher returns over variable cost than the fallow-sorghum system in Kadapa district (Table 5). The share of returns over variable cost in total household expenditure was also much higher in the case of the fallow-chickpea system than in the competing fallow-sorghum system. This clearly highlights the higher income security from chickpea than from sorghum crop in the district. The fallow-sorghum system was marginally better with respect to two indicators, chickpea equivalent fodder availability per acre and share of cereal consumption in total food production. Thus, overall, fallow-chickpea fared much better with respect to both productivity and other indicators of sustainability.

Even the returns over variable cost per hectare were higher for the fallow-chickpea system by 156% for the competing fallow-sorghum system in Anantapur district (Table 5). But the chickpea equivalent fodder availability per acre was decisively in favor of the fallow-sorghum system. The fallow-chickpea system

Table 5. Economic indicators of sustainability in chickpea study districts.								
	Prakasam district		Kurnool district		Kadapa district		Anantapur district	
Parameter	Fallow-Chickpea	Fallow-Maize (Equivalent yield to CP)	Fallow-Chickpea	Fallow-Sorghum (Equivalent yield to CP)	Fallow-Chickpea	Fallow-Sorghum (Equivalent yield to CP)	Fallow-Chickpea	Fallow-Sorghum (Equivalent yield to CP)
ROVC ($ per ha)	908.8	749.1	693.2	693.6	533.3	214.8	462.3	180.7
Chickpea equivalent fodder availability per acre (qtl)	3.0	16.9	3.0	49.8	4.0	44.6	4.0	59.0
Share of ROVC in total expenditure (%)	0.32	0.32	0.27	0.3	0.22	0.08	0.19	0.08
N/P ratio	0.46	2.7	0.55	1.1	0.55	1.27	0.46	0.76
Share of cereal consumption in total food production (%)	90.6	89.0	90.7	91.3	91.0	94.1	89.2	88.0

also reported a higher ratio of returns over variable cost in total expenditure than the competing fallow-sorghum system. The nitrogen-phosphorus ratio was more balanced in its case. It even reported a slightly higher share of cereal consumption in total food production than the fallow-sorghum system. The results clearly indicate that the household income chickpea security of chickpea farmers is higher than that for sorghum in the study district.

3.1.6. Resource-use efficiency and returns to scale

To learn about resource-use efficiency, production function was fitted to the farmers who raised JG 11. The Cobb-Douglas production function fitted and this explained about 84% of the variation in gross income from the farm (see Appendix-2 Table A9). Labor cost and machinery cost influenced gross income positively and significantly. A 1% increase in labor cost increases the gross income by 0.51%. Similarly, a 1% increase in machinery cost leads to an increase of 0.31% in gross income. Area of the farm also influenced the gross income positively and significantly. Fertilizer cost also influenced gross income positively, but it missed significance at the 5% level of probability. Bullock cost, seed cost, manure cost and pesticide cost did not have any significant influence on gross income, although they had weak negative effects. Input intensification may be feasible with labor, machinery, area and fertilizer, provided the marginal value products exceed their acquisition costs. The returns to scale add up to 1.22, indicating increasing returns to scale in case of chickpea cultivation with the JG 11 variety.

The Cobb-Douglas production function estimated for the *Kabuli* varieties, Vihar and KAK-2 also gave a good fit with a highly significant regression equation which explained the 97% variation in gross income (see Appendix-2 Table A10). Area of the farm, machinery cost and seed cost had a positive and significant influence on gross income. It may be possible to increase the gross income by increasing the area, machinery cost and seed cost. Manure cost and fertilizer cost did have a negative and significant effect on the gross income, suggesting that the gross income can be increased by reducing their use. Labor cost and pesticide cost did not have any significant effect on the gross income. The returns to scale added up to 1.01, indicating constant returns to scale in case of the *Kabuli* varieties.

The Cobb-Douglas production function fitted for sorghum gave a weak regression equation, explaining only 81% of the variation in gross income (see Appendix-2 Table A11). Area of the farm and irrigation cost had a positive and significant effect on gross income. None of the other variables had any significant influence on gross income. The returns to scale were estimated at 1.1.

In general, the returns to scale ranged between constant to increasing returns (Table 6). It was constant returns from *Kabuli* varieties, while there were increasing returns to scale in the case of the JG 11 variety. The returns to scale for sorghum ranged in between them.

Estimating inefficiencies in chickpea cultivation

The results of stochastic production function suggest that the area under the chickpea crop, expenditures on labor, machine labor and fertilizers impacted the production of the farm positively and significantly (see Appendix-2 Table A12). However, the expenditure on manures influenced the production negatively. The intercept values for Prakasam, Kurnool and Kadapa were negative and significant, suggesting that the production at zero levels of factors are lower for these districts when compared with the intercept value for Anantapur. Perhaps this is due to the higher response levels to the applied factors in these three districts. In the same way, the intercept value of production was lower in the case of uneducated farmers when compared with that for the educated group. Household head age, crop diversification index (CDI) and household network index (NWI) did not show any influence on chickpea production.

The average technical efficiencies of different categories of chickpea growers using the stochastic frontier production function are summarized in Table 7 for different districts and for the sample as a whole. The average technical efficiencies were lowest in Anantapur district, while they were the highest in Prakasam district. The average technical efficiencies of farmers in Kurnool and Kadapa districts lay in between. Large farmers attained the highest levels of technical efficiency in Anantapur and Kadapa districts relative to small and medium groups. But, in Kurnool and Prakasam districts, small farmers attained better levels of technical efficiency than the large and medium groups of farmers. The technical efficiency levels attained by the combined sample was only 0.57. Relative to the medium size group of farmers, both the small and large groups of farmers attained higher levels of technical efficiency in the combined sample.

3.1.7 Possible agronomic interventions for enhancing chickpea yields

In all the four districts, chickpea responded well to critical irrigation by registering higher yield levels (Figures 7a to 7d). In the same way, advancing the sowing date also resulted in higher yield levels. Farmers would get higher yields wherever they were able to advance the sowing date and wherever they could provide critical irrigation. Both these are potential agronomical interventions for enhancing chickpea yields across study districts.

Table 6. Returns to scale of chickpea and competing crop sorghum.

Crop	Returns to scale
Chickpea (JG-11)	1.22
Chickpea (Vihar/KAK2)	1.02
Sorghum	1.10

Table 7. Average technical efficiency by farmer category.

Farmer type	Anantapur	Kadapa	Kurnool	Prakasam	Average
Large	0.45	0.61	0.57	0.78	0.58
Medium	0.35	0.43	0.53	0.86	0.55
Small	0.45	0.45	0.64	0.93	0.59
Average	0.42	0.53	0.57	0.83	0.57

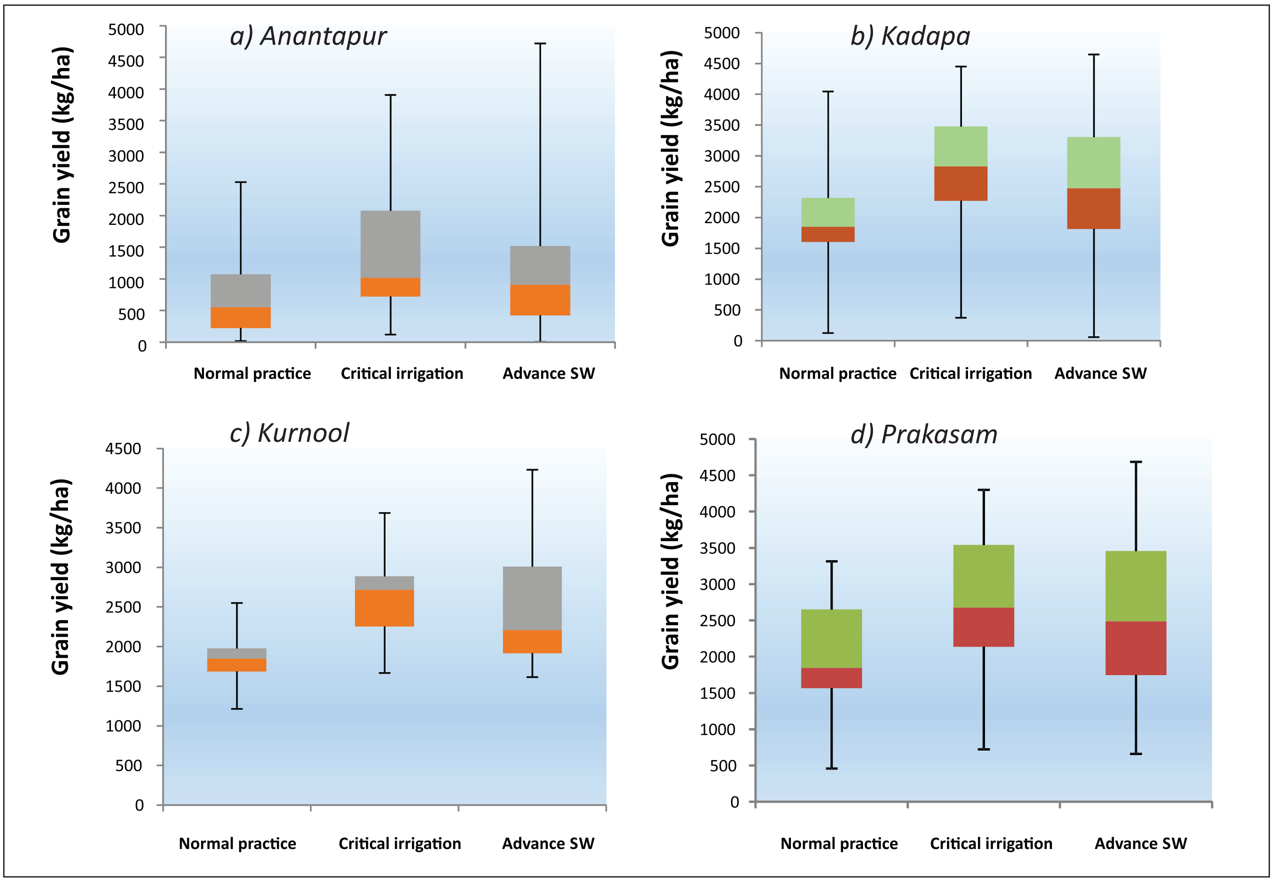

Figure 7. Response of chickpea yields to better agronomic practices.

Case 2. Rainy season sorghum in Maharashtra

Rainy sorghum cropping system was considered as a second case in the present study. Sorghum was one of the dominant *kharif* (rainy season) crops in the state of Maharashtra until the early 1990s. But the crop has last lost significant cropped area under sorghum between 1990 and 2011. However, the extent of adoption improved cultivars was in its peak up to > 95% (mostly hybrids). Due to lack of a market demand for the crop and changes in the food consumption pattern in the state, the importance for rainy sorghum has declined. It was replaced by other remunerative crops like soybean, cotton, and maize, etc. It would be interesting to study agricultural intensification and sustainability in Maharashtra.

3.2.1 Primary and secondary data sources analysis

As explained earlier, both primary and secondary data was used for assessing the agricultural intensification and sustainability in the study. The details of the primary household survey, sampling framework and its coverage are summarized in Appendix-2 (also see Kumara Charyulu et al. 2016a).

The declining share of rainy season sorghum in the net sown area is clearly illustrated in Figure 8 and Table 8. In Maharashtra, the share of rainy season sorghum was around 14% in 1966, which increased to 18% by 1977 (Figure 8). But after that, there was a gradual decline in its share to 5% in 2008, which slightly recovered to 6% in 2010. In all the important rainy season growing districts, the same trend was seen (Table 8). Rainy season sorghum in Latur district had a 39% share during the triennium 1990-92 which dropped to 24% in the triennium 2007-09. In the corresponding period, the share of rainy season sorghum dropped from 34% to 13% in Akola district; from 33% to 19% in Nanded district; from 25% to 7% in Amravati district; from 26% to 9% in Yavatmal; from 26% to 14% in Parbhani district and from 26% to 10% in Jalgaon. In the same way, rainy season sorghum lost its share in the net sown area of other districts like Sangli, Osmanabad, Satara, Dhule and Beed.

Table 8. Shares of rainy season sorghum in net sown area of selected districts.

District	1990-92	1999-01	2007-09
Akola	0.336	0.194	0.131
Amravati	0.254	0.152	0.074
Beed	0.131	0.113	0.048
Dhule	0.138	0.095	0.057
Hingoli	-	0.233	0.133
Jalgaon	0.257	0.175	0.096
Latur	0.392	0.315	0.242
Nanded	0.328	0.266	0.191
Parbhani	0.255	0.226	0.137
Sangli	0.229	0.206	0.130
Satara	0.153	0.119	0.087
Osmanabad	0.200	0.145	0.141
Yavatmal	0.261	0.182	0.090

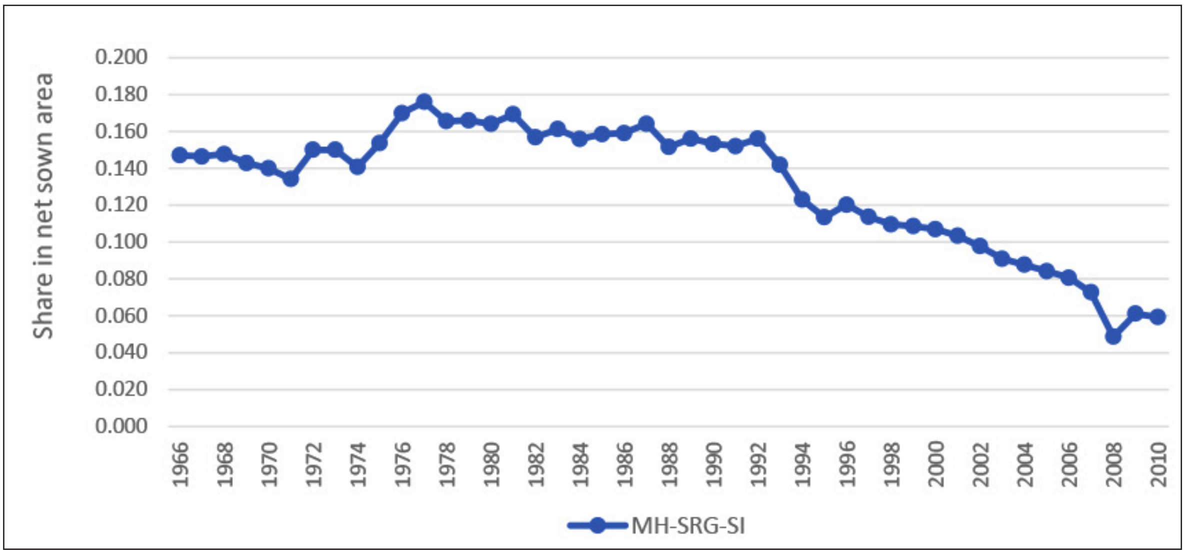

Figure 8. Share of rainy season sorghum in net sown area of Maharashtra.

The macro-trends illustrated in Figure 8 and Table 8 were evidently reflected in the case of the sample farmers in Figures 9 and 10. The area share of rainy season sorghum was less than 20% in the case of most of the farmers. It was higher than 20% only for some farmers. The area share of large farmers averaged around 17%, while that of medium category farmers was 25%. But, in the case of small farmers, this share is still higher at 33%, owing to their subsistence requirement.

3.2.2 Assessing sustainability using crop simulation models

The DSSAT CSM-CERES sorghum, CROPGRO-Chickpea and CROPGRO-Soybean models were used for the simulation studies. The cultivar used in the study was calibrated using the data of All India Coordinated Research Project (AICRP) on sorghum trials conducted across India (Singh et al. 2014b). Similarly, both chickpea (Singh et al. 2014a) and soybean cultivars were also well calibrated using AICRP multi-location trial data. The simulation results revealed that among the three alternate cropping systems available to the farmers, the soybean-chickpea system was the most profitable one. The soybean-chickpea system was the most productive system with about 13 tons of sorghum equivalent yield in terms of value. The

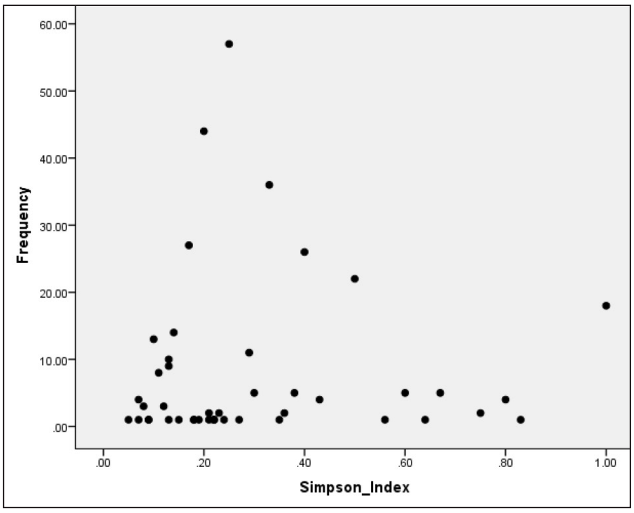

Figure 9. Intensification of sorghum among sample farmers (n=360).

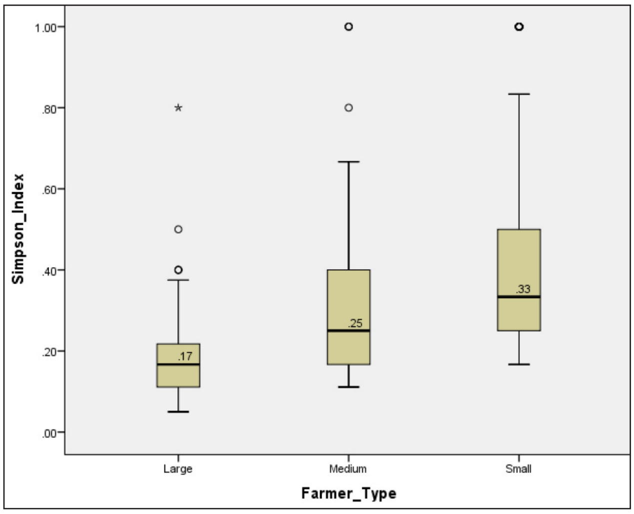

Figure 10. Intensification of sorghum by category of farmers (n=360).

sorghum-chickpea system gave 59% of the yield possible with the soybean-chickpea system (Table 9). The sorghum-fallow system was the lowest yielding system. The ranking of the systems remained the same with respect to both water-use efficiency as well as nitrogen-use efficiency. In terms of water-use efficiency, the sorghum-fallow system could give 48% of the efficiency attained by the soybean-chickpea system. The sorghum-chickpea system could reach up to 68% of the efficiency given by the best system. The soybean-chickpea system was 3.6 times more efficient than the sorghum-fallow system and 1.7 times more efficient than the sorghum-chickpea system in terms of nitrogen-use efficiency. The nitrogen leached during the crop season was the highest in the fallow-sorghum system, followed by the soybean-chickpea and sorghum-chickpea systems.

Nitrogen fixed during the cropping season was the highest in the legume-legume combination of the soybean-chickpea system. As one can expect, the sorghum-chickpea system fixed some nitrogen, while the sorghum-fallow system failed to fix any nitrogen. The same trend was noted with respect to inorganic nitrogen at maturity and crop nitrogen. The legume-legume system was better than the cereal-legume system, which, in turn, was better than the cereal-fallow system. However, the sorghum-chickpea system scored marginally better than soybean-chickpea system, while the sorghum-fallow system was far inferior to both these systems in terms of carbon dynamics. But total organic carbon at maturity was slightly higher in the case of the sorghum-chickpea system than in the case of the soybean-chickpea system. Thus,

Table 9. Sustainability of different cropping systems in Maharashtra.

Variables	Sorghum-Chickpea*	Soybean-Chickpea*	Sorghum-Fallow
Yield	7773	13180	3646
WUE	13.9	20.2	9.7
NUE	194.3	329.5	91.1
NLCM	3.0	3.6	5.5
NFXM	63.1	172.8	0.0
NIAM	18.7	45.0	6.6
CNAM	138.7	240.5	79.7
OCTAM	183522	175801	88182

Yield: kg/ha; WUE: Water-use efficiency (kg/ha mm); NUE: Nitrogen-use efficiency kg grain/kg N applied; NFXM: Nitrogen fixed during crop season (kg/ha); NLCM: Nitrogen leached during crop season (kg/ha); NIAM: Inorganic nitrogen at maturity (kg/ha); CNAM: Crop nitrogen uptake (kg/ha) and OCTAM: Total organic carbon at maturity stage (tons/ha)

*Soybean-chickpea/sorghum-chickpea yields represent sorghum equivalent yields the sorghum-chickpea system turned out to be the least profitable as well as least sustainable system. The sorghum-chickpea system occupied the intermediate position with respect to both profitability and sustainability. The best results in the case of both profitability as well as sustainability were obtained with the soybean-chickpea system.

3.2.3 Soil carbon simulations

The results of the simulation studies at the Parbhani location are presented in Appendix-2 Figure A7. The sorghum-fallow system was least efficient with respect to carbon dynamics. The sorghum-chickpea system turned out to be marginally superior to the soybean-chickpea system with respect to carbon dynamics. Perhaps a cereal-legume rotation is better than a legume-legume rotation with respect to carbon dynamics.

3.2.4 Assessment of economic sustainability of different systems

The returns over variable costs were quite insignificant in the case of the sorghum-fallow system, forming only 2% of the expenditure (Table 10). The sorghum-chickpea system was able to yield a respectable return over variable cost and it formed 36% of the expenditure. The soybean-chickpea system could give a bountiful return over variable cost, measuring up to 87% of the total household expenditure. The sorghum-fallow system yielded the highest fodder per acre, followed by the sorghum-chickpea system. The soybean-chickpea system fared the poorest only in the case of this indicator. The legume-legume system gave the best nitrogen-phosphorus ratio, while the sorghum-fallow system used the most nitrogen relative to phosphorus. All the three systems gave more or less the same share of cereal consumption in total food production.

In the case of Western Maharashtra, the soybean-chickpea system was not much in vogue and hence the comparison was restricted to the sorghum-chickpea system and the sorghum-fallow system (Table 10). On all the counts, the sorghum-chickpea system gave a better performance with the exception of the nitrogen-phosphorus ratio. It gave higher yields; gave significant returns and had higher water and nitrogen use efficiencies. Both the systems were at par with respect to the share of cereal consumption in total food production.

In the Vidarbha region, all the three systems discussed in the case of Marathwada were in vogue. The results were also similar to those obtained in Marathwada (Table 10). Both the efficiency indicators, yield, returns over variable costs and share of ROVC in total expenditure as well as sustainability indicators, water-use efficiency, nitrogen-use efficiency and nitrogen-phosphorus ratios were the most desirable in the case of the soybean-chickpea system. The sorghum-chickpea system scored better with respect to fodder availability per acre. All the three systems were at par with respect to the share of cereal consumption in total food production.

3.2.5 Resource-use efficiency and returns to scale

The explanatory power of the Cobb-Douglas production function was quite high in the case of soybean, while it was moderate in the case of chickpea and sorghum (see Appendix-2 Tables A14 to A16). But all the three equations were statistically significant. In the case of sorghum function, area under the crop, expenditures on human labor, bullock labor, machinery, pesticides and manures had significant impacts on the gross returns. Expenditures on seed and fertilizer did not influence returns significantly. In the case of the production function for soybean, the area under the crop and the expenditures on seed and pesticides influenced the gross returns significantly. It is important to note that the traditional inputs like human labor, machine labor, bullock labor and manures were important in the case of sorghum production. In the case of chickpea, both cropped area and extent of labor cost per acre were significant at the one and 5% level respectively. Seed cost also showed significance but at the 10% level only. For both sorghum and soybean, use of hybrid seed was near universal and there was not much variability in seed costs. But it is significant that seed and pesticide investments had significant impacts on gross returns in the case of soybean.

It is heartening to note that the returns to scale were more than one for all the three study crops (Table 11). But it is surprising that sorghum yielded the highest returns to scale, relegating soybean to the third place. Chickpea occupied the middle position in between them. The most profitable crop, soybean, recorded the lowest returns to scale.

Estimation of inefficiencies in sorghum cultivation

The results of the stochastic production function for sorghum for Maharashtra are presented in Appendix-2 Table A17. The expenditures on labor, machinery and seed had positive impacts on efficiency, while those on manures and fertilizers had negative effects on efficiency and production. The household network index (NWI) impacted production efficiency positively. The crop diversification index (CDI) did not show any significant influence on sorghum production. There are no significant differences in technical efficiencies among the three study regions. Other social variables such as age and, education showed no impact on the sorghum efficiency.

The technical efficiency of sorghum growers across three regions were estimated using the stochastic frontier production function and summarized in Table 12. The estimates of production efficiency for sorghum in different regions of Maharashtra were fairly high. Production efficiency was relatively higher in the Western Maharashtra region. It was lower in Marathwada, with Vidarbha occupying the intermediate position. Medium-sized farms in Marathwada and Western Maharashtra and large-sized farms in Vidarbha were relatively more efficient. Small farms were least efficient on an average when compared with the other two groups.

Table 10. Economic sustainability indicators of sorghum in Maharashtra.

	Marathwada region			Western MH region		Vidarbha region		
Parameter	Sorghum-chickpea	Soybean-chickpea	Sorghum-fallow	Sorghum-chickpea	Sorghum-fallow	Sorghum-chickpea	Soybean-chickpea	Sorghum-fallow
ROVC ($ per ha)	515	1239	35	543	63	534	1231	54
Sorghum equivalent fodder availability per acre (qtl)	42.1	9.3	42.8	52.6	33.8	47.4	11.8	39.6
Share of ROVC in total expenditure (%)	0.36	0.87	0.02	0.40	0.04	0.47	0.62	0.04
N/P ratio	1.2	0.88	1.46	1.64	1.53	1.42	1.03	1.46
Share of cereal consumption in total food production (%)	86.0	88.0	86.0	90.0	90.0	86.0	88.0	86.0

Table 11. Returns to scale of rainy season sorghum and competing crops.

Crop	Returns to scale
Sorghum	1.37
Chickpea	1.24
Soybean	1.10

Table 12. Average technical efficiency by farmer category.

Farmer type	Marathwada	Western Maharashtra	Vidarbha	Average
Large	0.89	0.91	0.92	0.90
Medium	0.90	0.93	0.89	0.91
Small	0.86	0.90	0.90	0.88
Average	0.88	0.92	0.90	0.90

3.2.6 Possible agronomic interventions for enhancing sorghum yields

The sorghum-fallow system was less efficient than the sorghum-chickpea system (Figure 11). So, it is better that the farmers take-up chickpea after sorghum, wherever possible. In case of both the sorghum-fallow and sorghum-chickpea systems, farmers would be better-off following improved practices (application of recommended dose of nitrogen, 80 kg/ha) than sticking to their traditional practices (40 kg/ha).

Case 3: Pearl millet in Maharashtra

Pearl millet cropping systems in the state of Maharashtra was selected as a third case in the present study. Pearl millet was one of the dominant rainy season crops in the Western Maharashtra and Marathwada regions until the early 2000s. It has lost significant cropped area during the last decade because of severe competition from cotton and maize crops. Low market demand and changes in food consumption habits limited its cultivation in the state. However, it has due recognition and importance in selected parts of the state (like the western region) because of its high demand for consumption as grain and as fodder for livestock. It would be another interesting case to highlight the issues of intensification and sustainability in the state.

3.3.1 Primary and secondary data sources analysis

As indicated earlier, both primary and secondary data sources of information were used to assess agricultural intensification and sustainability in the case of pearl millet in Maharashtra. The details about study sampling framework, study locations and details about sample are summarized in Appendix-2 (also see Kumara Charyulu et al. 2016b).

Just as in the case of rainy season sorghum, pearl millet also lost the area under it over the years. The area share of pearl millet in the net sown area of Maharashtra has shown a decline (Figure 12). In 1966, it had a share of 9.5% and it initially went up to 12% by 1969. Its share was 12% in 1973, but steadily dropped over time to reach 5.5% in 2008 before recovering to 6% in 2010. In all the nine important pearl millet growing districts of Maharashtra, the area share of pearl millet dropped over time (Table 13), with the exception of Dhule district. The share of pearl millet was 29.3% in Ahmednagar district during the triennium of 1990-92 (average), and fell to 23.9% in the triennium of 1999-2001 (average) and further to 16.6% in the triennium of 2007-09 (average). In Nashik district, pearl millet had a high share of 40.5% in 1990-92 (average), but it came down to 22.3% in 2007-09 (average). The declining trend was visible in six other districts as well. It fell from 25.9% to 16.5% in Aurangabad district; from 20.8% to 19.1% in Beed district; from 13.4% to

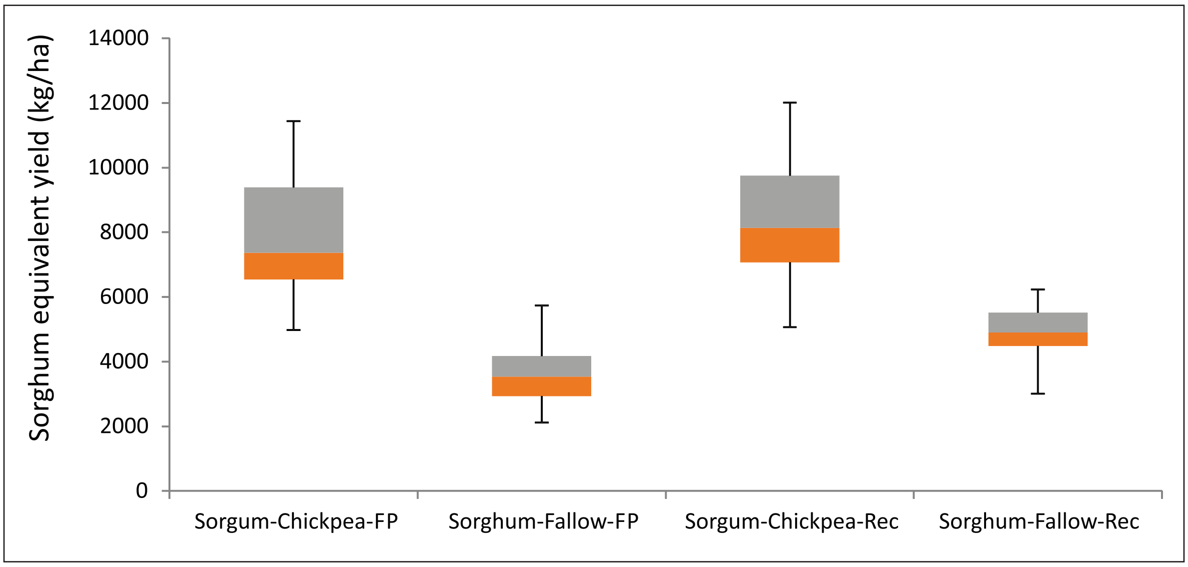

Figure 11. Sorghum performance under management practices (FP/IMP).

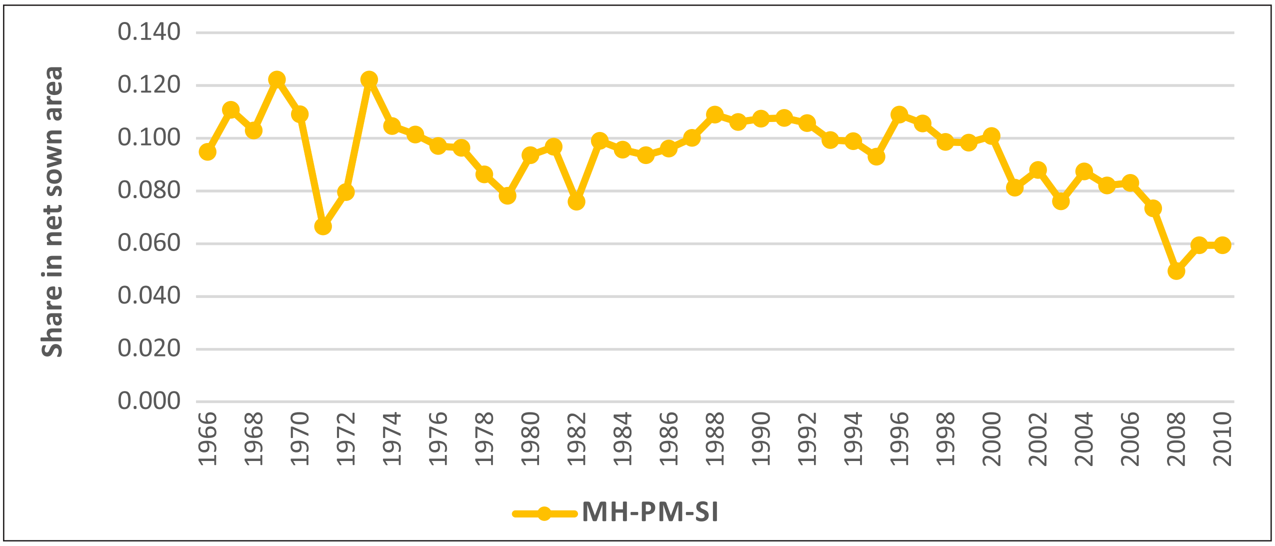

Figure 12. Share of pearl millet in net sown area of Maharashtra.

Table 13. Share of pearl millet in net sown area of selected districts in Maharashtra.

Triennnium	Ahmednagar	Aurangabad	Beed	Dhule	Jalgaon	Nashik	Pune	Sangli	Satara
1990-92	0.293	0.259	0.208	0.219	0.134	0.405	0.202	0.162	0.185
1999-01	0.239	0.207	0.281	0.316	0.079	0.396	0.149	0.139	0.146
2007-09	0.166	0.165	0.191	0.258	0.049	0.223	0.071	0.084	0.101

4.9% in Jalgaon district; from 20.2% to 7.1% in Pune district; from 16.2% to 8.4% in Sangli district; and from 18.5% to 10.1% in Satara district. But in Dhule district, the area share of pearl millet in net sown area increased from 21.9% in 1990-92 (average) to 31.6% in 1999-2001 (average), but fell to 25.8% in 2007-09 (average).

The results of the Simpson index (Figure 13) have shown that the area share of pearl millet was as low as 20% in the case of large farmers (average). The medium sized farms in the sample, on an average, had allocated a share of one third to pearl millet. But small farmers, owing to their subsistence requirements continued to allocate about one half of their net sown area to pearl millet. The scatter diagram of the shares allocated by sample farmers showed that the bulk of the farmers allocated less than 20% of their net sown area to pearl millet (Figure 14). But, in a few cases, the area shares allocated by sample farmers touched up to 60%.

3.3.2 Assessment of pearl millet sustainability using simulation models

Due to the lack of a well calibrated model for pearl millet in Maharashtra, crop simulations were not attempted to assess sustainability. However, sustainability analysis was attempted using data collected at the sample farmers' level.

3.3.3 Economic sustainability of pearl millet

In Marathwada region, maize-fallow and cotton-fallow systems compete for land with the pearl millet-fallow system (Table 14). The maize-fallow system was the most profitable system, with the returns over variable cost reaching up to 50% of the total expenditure. This ratio was 0.26 in the case of cotton-fallow system and was only 0.04 in the case of the pearl millet-fallow system. Farmers were just able to recover the variable costs in the case of pearl millet, while maize and cotton returned reasonable profits. Pearl millet scored marginally better only in the case of fodder availability per acre but this was still less than the maize-fallow competing system. The share of cereal consumption in total food production was also slightly

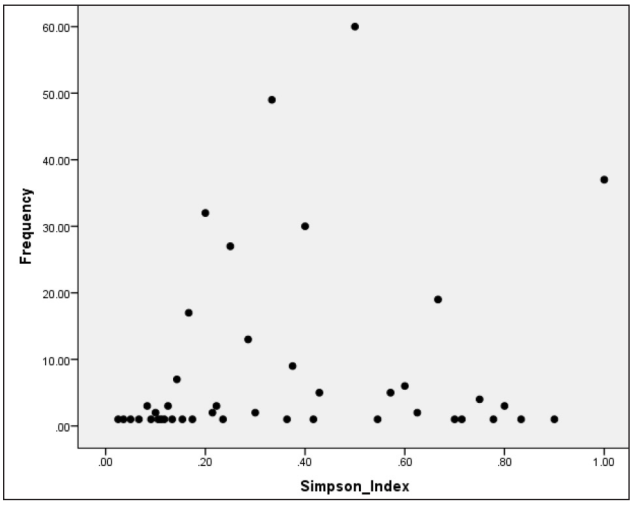

Figure 13. Intensification of pearl millet among sample farmers (n=360).

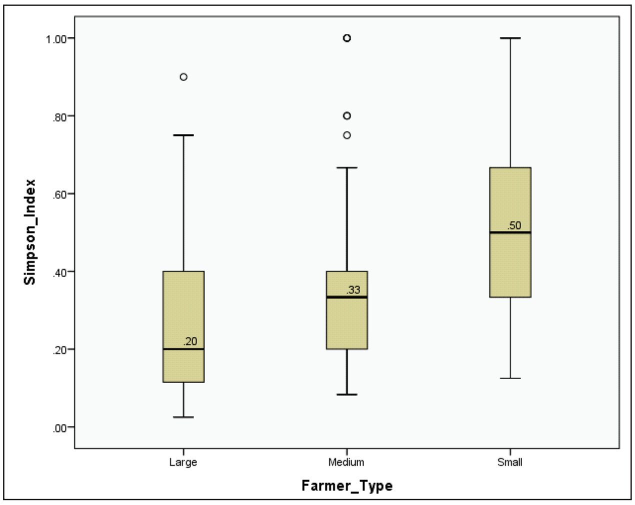

Figure 14. Intensification of pearl millet by category of farmers (n=360).

higher in the case of pearl millet. But, even the nitrogen-phosphorus ratio was unfavorable in pearl millet. Perhaps this was due to the fact that, only nitrogen was applied to pearl millet, while the competing crops received a more balanced use of fertilizers. Overall, pearl millet scored very low in terms of profitability, while the sustainability indicators gave mixed signals.

The results were similar in the Western Maharashtra region also (Table 14). Pearl millet was the least profitable, while maize was the most profitable, with cotton occupying the middle position. Pearl millet was just able to return the variable costs with a negligible surplus of 8%. Cotton gave a return of 18%, while maize gave a decent return of 35% in the total expenditure. Even the pearl millet equivalent fodder availability per acre was higher for maize than for pearl millet. Pearl millet was only able to give a desirable nitrogen-phosphorus ratio better than that of the two competing crops. The share of cereal consumption in total food production was higher with maize than with pearl millet. Thus, pearl millet was least profitable and did not have superiority even in case of sustainability indicators.

3.3.4 Resource-use efficiency and returns to scale

Table 14. Economic indicators of pearl millet sustainability.

	Marathwada region			Western Maharashtra region		
Parameter	Pearl millet-fallow	Maize-fallow	Cotton-fallow	Pearl millet-fallow	Maize-fallow	Cotton-fallow
ROVC ($ per ha)	85.9	906.6	468.8	146.2	607.6	306.0
Pearl millet equivalent fodder availability per acre (qtl)	23.0	44.0	-	22.0	26.5	-
Share of ROVC in total expenditure (%)	0.04	0.50	0.26	0.08	0.35	0.18
N/P ratio	2.5	1.7	1.2	0.45	2.2	0.56
Share of cereal consumption in total food production (%)	25	25	20	26	35	22

The explanatory power of the production function for pearl millet was rather poor, while those of cotton and maize were moderate (see Appendix-2 Tables A19 to A21). The expenditure on human labor, bullock labor, machine labor and fertilizers had a statistically significant and positive effect on production in the case of pearl millet. In the case of cotton, the expenditure on human labor, seed and pesticides did have a positive and significant influence on production, while the expenditure on bullock labor impacted production negatively. The expenditure on bullock labor, machinery and seed had positive and significant impacts on maize production, while the expenditure on irrigation had a negative effect.

For all the three crops, ie, pearl millet, cotton and maize, the returns to scale were increasing (Table 15). They were significantly higher than one at 1.35 in the case of pearl millet, while they were too high and close to two in the case of the competing crops, cotton and maize.

Estimation of inefficiencies in pearl millet cultivation

The expenditure on human labor and machinery contributed to the production efficiency of pearl millet positively and significantly (see Appendix-2 Table A22). The dummy variables for crop diversification index (CDI) and network index (NWI) and region (Marathwada /Western Maharashtra) had positive and significant values, suggesting that these variables had higher intercept values, while the dummy variable for education had a negative and significant value, implying that the educated farmers had a lower intercept value.

The average values of technical efficiency attained in pearl millet production by region and farmer category are furnished in Table 16. Among the regions, Western Maharashtra had attained slightly higher levels of technical efficiency than the Marathwada region. Among the farm size categories, large farmers attained higher levels of technical efficiency in pearl millet production, while the small farmers were far behind in efficiency.

Comparison of indicators across crops

The estimated sustainable intensification indicators are summarized across three case studies and presented in Table 17. As explained in the earlier sections these values were estimated at respective cropping system level in the study locations rather than at firm level. It will be more appropriate to compare each cropping system values with respective competing cropping system existed in that study location. It would be misleading if we compare these values across crops and study locations.

Table 15. Returns to scale in case of pearl millet and competing crops.

Crop	Returns to scale
Pearl millet	1.35
Cotton	1.95
Maize	1.99

Table 16. Average technical efficiency in Pearl millet production by farmer category and region.

Farmer type	Marathwada	WMH	Average
Large	0.50	0.67	0.63
Medium	0.53	0.61	0.59
Small	0.56	0.54	0.54
Average	0.54	0.58	0.57

Table 17. Comparison of intensification and sustainable indicators across three case studies.

Approach	Indicator	Chickpea in AP*	Sorghum in MH@	Pearl millet in MH#
Intensification				
Geospatial analysis	MODIS NDV values	Increasing over time	NA	NA
Primary data	Simpson index	0.80 to 1.00	0.20	0.20
Secondary data	% share in net sown area over time	Increasing trend	Declining trend	Declining trend
Crop simulation models	Crop yield	3662	7773	NA
	WUE	7.4	13.9	NA
	OCTAM	133	183522	NA
	NUE	183.1	194.3	NA
	NFXM	136.4	63.1	NA
	NLCM	46.9	3.0	NA
	NIAM	85.5	18.7	NA
	CNAM	168.5	138.7	NA
Econometric models	Returns to scale	1.22	1.37	1.35
	Technical efficiency	0.83	0.88	0.54
Economic indicators	ROVC ($ per ha)	908.8	515	146.2
	Respective crop equivalent fodder availability/acre	3.0	42.1	22.0
	Share of ROVC in total expenditure (%)	0.32	0.36	0.08
	N/P ratio	0.46	1.2	0.45
	Share of cereal consumption in total food production (%)	90.6	86.0	26.0

NA: not applicable

* refers to Fallow-chickpea system at Prakasam district of Andhra Pradesh state

@ refers to sorghum-chickpea system at Marathwada region of Maharashtra state

refers to pearl millet-fallow system at Western MH region of Maharashtra state

4. Farmer Perceptions and Drivers of Agricultural Sustainability

Perceptions of the primary household survey farmers were also recorded to know about the drivers (socio-economic, bio-physical, etc) and incentives required to motivate farmers to adopt agriculturally sustainable agricultural practices in different cropping systems. The household indicators estimated fed to principal components analysis (PCA). The generated PCA components are furnished in Figures 15 to 17 respectively.

4.1. Chickpea in Andhra Pradesh state

The intensity of input use in terms of expenditures incurred on various inputs was measured over a period of one decade (Table 18). The cost of input use one decade ago was inflated to the present day to make the comparisons. The input use intensity has increased in all the districts with respect to virtually all the inputs. The pooled data for fertilizer use reflected a 61% increase over the past decade. The practice of giving irrigation support has gained ground. The expenditure on irrigation has increased by 688%. The own land allocation has increased from seven to 12 acres, while that of leased land allocation has quadrupled from three to 12 acres. Many farmers leased land to increase the scale of operation in chickpea cultivation.

The expenditure on mechanization reported a 42% increase. Similarly, the expenditure on pesticides has increased by 55%. Very few farmers invested in soil and water conservation. Those who invested made substantial investments to the tune of INR 15,000 per farm. This expenditure was a paltry INR 33 a decade ago. The pattern of input use reflected a massive intensification in chickpea cultivation in Andhra Pradesh. Both the own land as well as leased land allocation increased several fold as chickpea cultivation was profitable for the farmers.

Drivers of chickpea sustainable intensification across study districts (PCA Coefficients)

Some drivers of sustainable intensification of chickpea in the four study districts of Andhra Pradesh were noted through the web diagram drawn (see Figure 15). The returns exceeding the variable cost was an important driver for intensification in a specific geographic location. Food expenditure to returns over the variable cost, animal to fodder ratio, nitrogen-phosphorus ratio and cereal to grain ratio were the other factors driving sustainability. But, the specialization in chickpea has led to reduced crop diversification index. The socio-cultural variables like network index, age and education also had limited impacts on intensification. The specific sustainability perceptions of farmers in chickpea cultivation in Andhra Pradesh were not collected in the primary household survey.

4.2. Rainy Sorghum in Maharashtra state

In Maharashtra, farmers reduced their own land allocation to rainy season sorghum over the last decade (Table 19). The pooled data revealed that the farmers have cut their land allocation by one half. It was quite rare for the farmers in Maharashtra to lease land for cultivating sorghum in the rainy season. Only 4% of the sample farmers leased land for sorghum cultivation but they increased the leased area by one-third. Apart from land allocation, farmers have intensified the input use even in the case of rainy season sorghum. Due to the universal use of hybrids, the seed rate decreased from five kg to three kg per acre. But the fertilizer use per unit area nearly doubled in the pooled sample. The use of fertilizer was relatively higher in Western Maharashtra than in the other two regions, Vidarbha and Marathwada. Irrigation

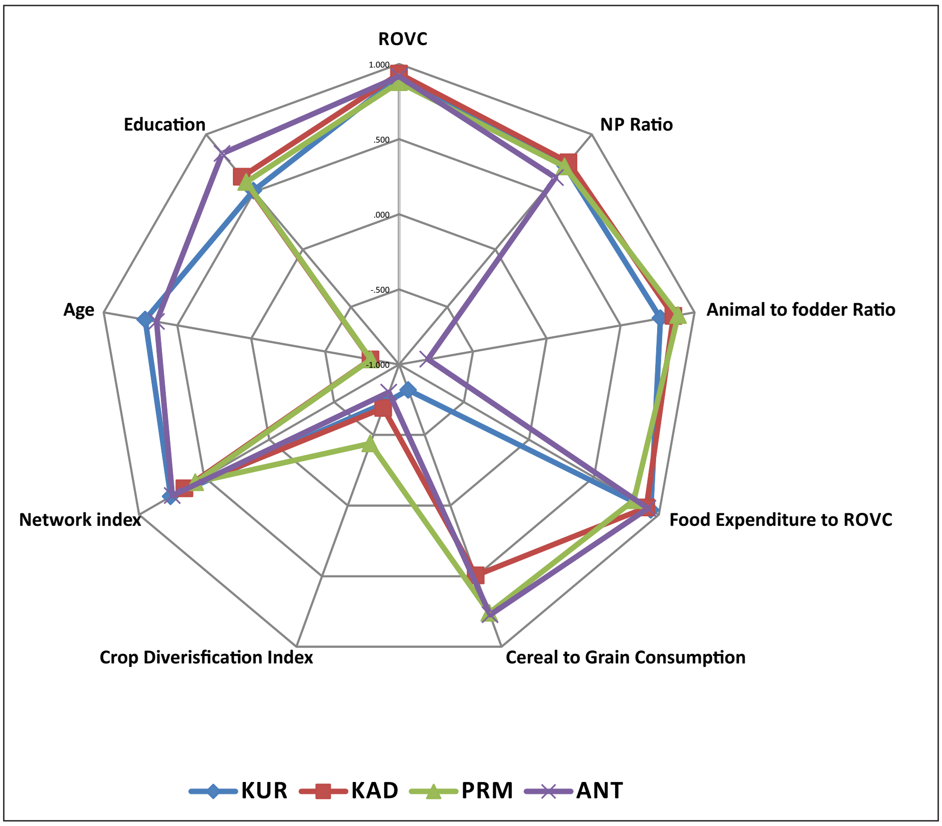

Figure 15. Drivers of agricultural intensification of chickpea in study districts.

Table 18. Adoption of chickpea improved technologies and change in input-use behavior over last decade.

Indicators	Anantapur		Kadapa		Kurnool		Prakasam		Pooled	
	Old allocation*	Current allocation	Old allocation*	Current allocation	Old allocation*	Current allocation	Old allocation*	Current allocation	Old allocation*	Current allocation
Fertilizer application cost	685 (134)	1055	884 (124)	1413	926 (349)	1467	1091 (107)	1877	898 (714)	1442
Irrigation expenditure	0 (1)	13000	0	0	0	0	1015 (2)	1500	677 (3)	5333
Leased-in land allocation	3.5 (15)	16	0 (7)	11	3 (69)	12	2 (45)	11	3 (136)	12
Mechanization	1747 (134)	2175	2162 (124)	2789	1522 (342)	2178	1645 (106)	2952	1695 (706)	2401
Own land allocation	7 (26)	13	6 (14)	11	8 (134)	14	3 (40)	6	7 (214)	12
Pesticide application cost	687 (134)	994	726 (124)	1087	866 (349)	1343	860 (107)	1434	807 (714)	1247
Soil & water conservation expenditure	0 (3)	10000	0 (1)	20000	0 (3)	28000	146 (2)	700	33 (9)	15044

Note: Figures in the parentheses represent no. of respondents
* Costs are inflated to 2009-10 prices

Table 19. Adoption of sorghum (rainy) improved technologies and change in input-use behavior over last decade.

Indicator	Marthawada		WMH		Vidarbha		Pooled	
	Old allocation*	Current allocation	Old allocation*	Current allocation	Old allocation*	Current allocation	Old allocation*	Current allocation
Fertilizer application cost (kg/acre)	66 (144)	125	62 (62)	146	61 (61)	113	64 (267)	127
Irrigation expenditure (Rs/acre)	425 (19)	1353	932 (9)	1422	400 (1)	0	581 (29)	1328
Leased-in land allocation (acres)	2 (5)	4	7 (1)	5	3 (2)	2	3 (8)	4
Mechanization (Rs/acre)	541 (151)	1147	554 (75)	995	508 (68)	972	536 (294)	1068
Own land allocation (acres)	4 (118)	2	4 (49)	2	5 (49)	2	4 (216)	2
Pesticide application cost (Rs/acre)	141 (119)	191	149 (28)	259	120 (47)	144	137 (194)	189
Seed rate (kg)	5 (123)	3	5 (52)	3	4 (57)	5	5 (232)	3
Soil & water conservation exp. (Rs/acre/year)	393 (80)	803	332 (41)	454	335 (41)	510	363 (162)	640

Note: Figures in the parenthesis represents no. of respondents
* Costs are inflated to 2010-11 prices

support is rarely provided to rainy season sorghum. But, in Marathwada, this practice is gaining popularity. Some farmers in Western Maharashtra are also providing it, while it is rarely practiced in the Vidarbha region. But those who provided the irrigation support incurred higher expenditures than a decade ago. The pooled data showed that the irrigation expenditure went up by 129%. Mechanization has become the order of the day and the farmers are spending twice the amount for it now when compared to the amount spent a decade ago. The expenditure on pesticides has gone up by 38%. A substantial number of sample farmers are making investments on soil and water conservation. The expenditure on this count also has gone up by 76%. Thus, the farmers have, in general, increased the input use to realize higher yields, even when the crop is not very profitable. But, the farmers are reducing the area under the crop over time as it is relatively less profitable.

It is very difficult and expensive to assess the sustainability of resources like land and water, which are critical to agriculture. A number of tests have to be carried out to know about the long term sustainability of agriculture and they require huge financial and manpower resources. In the absence of those resources, the survey included questions on some indicators of sustainability. The farmers' perceptions were recorded and some broad conclusions were drawn about the agricultural sustainability on the basis of the analysis of the farmers' perceptions (Table 20).

Many of the perceptions are ringing danger bells to agricultural sustainability. The average size of holding has decreased; the availability of fodder/grazing pastures has declined; the livestock population has fallen; land allocation to food crops has decreased; application of farm yard manure or other organic matter has decreased; and the soil fertility status has worsened. The intensity of cropping and use of legumes in crop rotation have improved and the application of inorganic fertilizers has gone-up. These positive features failed to stem the decline in the fertility status of the soil. Use of farm machinery and pesticides has also increased and this can only have deleterious effects on agricultural sustainability. One positive feature was the increase in investments for soil and water conservation, but it has also failed to arrest the soil erosion problem. Many other aspects like cultivation of green manure crops, micro-nutrient application

Table 20. Perceptions of sorghum sample farmers about agricultural sustainability (N=360).

	Pooled (% of HH)		
Indicator	Increased	Constant	Decreased
Livestock population (No. per Hh)	1.7	7.8	90.6
Availability of fodder/grazing pastures	0.8	17.5	81.7
Area under green manure crops	16.4	81.4	2.2
Land allocation for food crops (acres)	0.6	45.0	54.4
Average land holding size of farm (acres)	1.4	19.2	79.4
Land-use intensity (no. of crops per year)	69.2	30.0	0.8
Use of legumes in crop-rotations/inter-cropping	54.2	16.4	29.4
FYM/other organic matter application rate (qtl/acre/year)	3.6	8.1	88.3
Soil and water conservation investments per acre (private and public)	53.3	46.4	0.3
Soil loss due to erosion	91.9	2.8	5.3
Soil fertility status (organic carbon and NPK levels)	0.3	5.0	94.7
Inorganic fertilizers (N, P, K - application rate)	83.6	12.8	3.6
Micronutrient application (kg/acre)	26.7	73.1	0.3
Frequency of soil testing and use of fertilizers based on recommendations	24.7	75.0	0.3
Expenditure on plant protection chemicals (Rs./acre)	71.1	26.7	2.2
Expenditure on farm mechanization (Rs./acre)	100.0	0.0	0.0

and frequency of soil testing remained at the same level as earlier. The overall impression one gains after reviewing the farmers' perceptions is that agricultural sustainability is at risk. The farmers growing rainy season sorghum perceive a threat to long-term productivity and soil fertility.

Drivers of sustainable Intensification of sorghum in Maharashtra (PCA Coefficients)

Among the three regions of Maharashtra, Western Maharashtra seems to be better placed in terms of crop diversification index**,** nitrogen-phosphorus ratio**,** fodder to animal ratio, cereal to grain consumption and network index (Figure 16)**.** Marathwada seems to be better placed with respect to education and food expenditure to return over variable costs. Vidarbha scored in age. All the three regions seem to be at par with respect to the returns over variable costs. All these factors are influencing the agricultural intensification.

4.3. Pearl millet in Maharashtra state

Just as in case of rainy season sorghum, the sample farmers in both Marathwada and Western Maharashtra have reduced the own land allocation to pearl millet from three to two acres per farm (Table 21). Leasing land to cultivate pearl millet is rather unusual in both Marathwada as well as in Western Maharashtra. Only a couple of farmers have leased land to cultivate pearl millet and they have also reduced the leased land allocation to pearl millet. Farmers are adopting mostly hybrids due to which the seed rate was reduced from four kg to two kg per acre. But, input use intensity has increased in case of fertilizer, machinery use and pesticide application. The expenditure on fertilizer increased by 147%, while that on machinery increased by 64%. The cost of pesticide application has increased by 184%. A dozen farmers invested in soil and water conservation. They have increased the investments on soil and water conservation by twenty times.

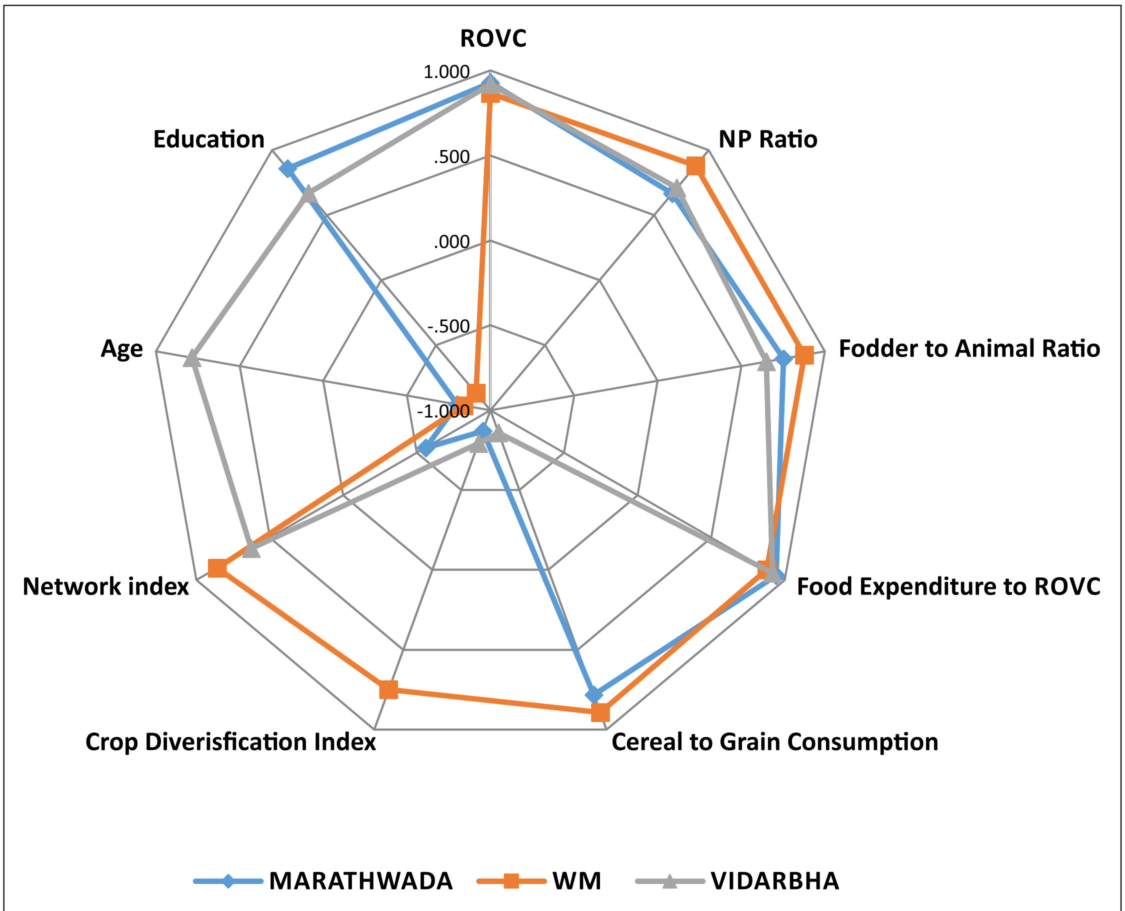

Figure 16. Drivers of sorghum agricultural intensification across regions.

Table 21. Adoption of pearl millet improved technologies and change in input-use behavior over last decade.

	Marathwada		Vidharbha		Pooled	
Indicators	Old allocation*	Current allocation	Old allocation*	Current allocation	Old allocation*	Current allocation
Fertilizer application cost (Rs/acre)	647 (86)	1510	527 (238)	1336	559 (324)	1382
Leased-in land allocation (acres)	0 (1)	1	15 (1)	10	8 (2)	6
Mechanization (Rs/acre)	1147 (82)	1762	919 (230)	1545	978 (312)	1602
Own land allocation (acres)	3 (31)	2	3 (88)	2	3 (119)	2
Pesticide application cost (Rs/acre)	236 (2)	350	149 (12)	475	161 (14)	457
Seed rate (kg)	4 (30)	2	3 (146)	2	4 (176)	2
Soil & water conservation exp. (Rs/acre/year)	0 (6)	1200	138 (6)	1668	69 (12)	1433

Note: Figures in the parenthesis represents no. of respondents
*all costs are inflated to 2010-11prices

In contrast to the perceptions of farmers growing sorghum in the rainy season, pearl millet farmers indicated that the indicators of sustainability have largely improved over a period of time (Table 22). About 56% of the sample farmers opined that their soil fertility status has improved. Many of them were able to increase the use of farm yard manure and other organic manures, besides the application of inorganic fertilizers and, hence, were able to perceive an improvement in the status of soil fertility. They have increased the use of farm machinery which is now as much as it is anywhere else. A good

Table 22. Perceptions of pearl millet sample farmers about agricultural sustainability (N=360).

	Pooled (% of HH)		
Indicator	Increased	Constant	Decreased
Area under green manure crops	1.9	64.2	33.9
Availability of fodder/grazing pastures	32.5	42.2	25.3
Average land holding size of farm (acres)	3.3	68.1	28.6
Expenditure on farm mechanization (Rs/acre)	92.5	6.4	1.1
Expenditure on plant protection chemicals (Rs/acre)	30.0	49.4	20.6
Freq. of soil testing and use of fertilizer based on recommendation	25.3	54.4	20.3
FYM/other organic matter application rate (qtl/acre/year)	55.3	32.5	12.2
In-organic fertilizers (N,P,K) application rater (kg/acres)	76.4	20.6	3.1
Land allocation for food crops (acres)	10.0	50.3	39.7
Land-use intensity (No. of crops/year)	29.2	61.4	9.4
Livestock population (No./HH)	20.3	46.1	33.6
Micro-nutrient application (kg/acre)	11.9	77.2	10.8
Soil and water conservation investment per acre(pri.+Publ)	29.2	52.8	18.1
Soil fertility status (Organic carbon and NPK levels)	56.4	21.9	21.7
Soil loss due to erosion	15.8	26.4	57.8
Use of legumes in crop-rotation/inter-cropping	13.6	64.2	22.2

proportion of them invested more in soil and water conservation but yet the soil loss due to erosion continued to increase. Pearl millet farmers, by and large, perceived constant status with respect to several indicators like livestock population, area under green manure crops, use of legumes in crop rotation/ inter-cropping, average size of holding, land use intensity, land allocation to food crops, micro-nutrient application, availability of fodder/grazing pastures, frequency of soil testing, expenditure on other plant protection chemicals etc., Despite some indicators showing weakness, the pearl millet sample farmers in Maharashtra perceived that, by and large, sustainability indicators are showing an improvement over time.

Drivers of pearl millet agricultural intensification in Maharashtra (PCA coefficients)

Among the different indicators of agricultural sustainability, both the study regions scored poorly with respect to crop diversification index and education (Figure 17). Marathwada scored better with respect to network index and nitrogen-phosphorus ratio. Western Maharashtra was better placed with respect to cereal to grain consumption and fodder to animal ratio. Both these regions were at par with respect to returns over variable costs and food expenditure to returns over variable costs.

5. Conclusions and the way forward

This study tried to look at the scope for sustainable intensification in Semi-arid Tropics of India, with three data sets relating to i) chickpea in Andhra Pradesh, ii) rainy season sorghum in Maharashtra and iii) rainy season pearl millet in Maharashtra. There may be a limited scope for increasing the use of inputs for realizing higher yields without impairing the longer term productivity of the critical resources. Sustainable intensification precisely looks at these limited opportunities. Its scope is specific to a given region and a given cropping system. It may be possible to exploit opportunities for sustainable intensification by altering the cropping systems. Or, new technologies may enhance this scope for sustainable intensification. The present study looked at the three examples and assessed the scope for sustainable intensification.

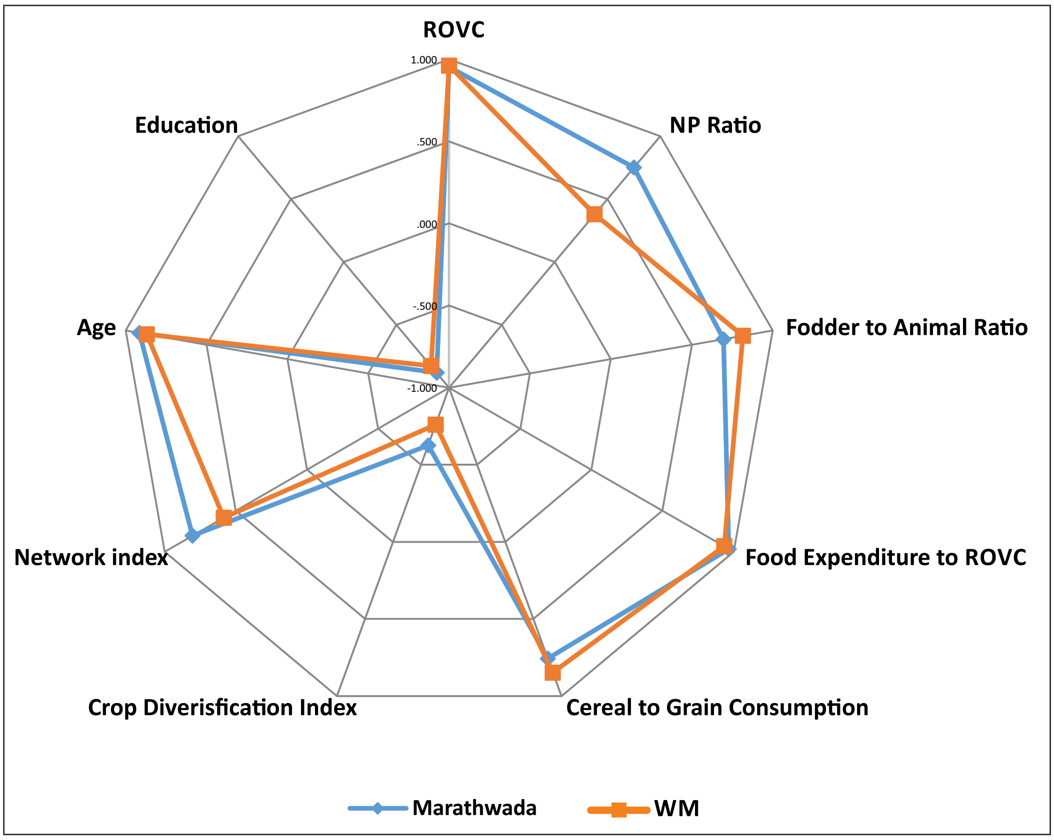

Figure 17. Drivers of sustainable intensification across regions (PCA Coefficients).

The first case of chickpea in Andhra Pradesh provides an ideal scenario for sustainable intensification. Chickpea is more productive than the competing crops of maize and sorghum during the post-rainy season. At the same time, it has also scored better with respect to sustainability indicators like water-use efficiency, nitrogen-use efficiency, organic carbon dynamics, etc. But, it may have met other sustainability indicators like fodder availability, food security etc. only partially. Because of the productivity and sustainability of chickpea, the area share of chickpea went-up in almost all the important chickpea growing districts of Andhra Pradesh. Some more scope might exist for extending the process of sustainable intensification of chickpea. But the availability of water retentive heavy soils might be getting exhausted in the chickpea growing districts to limit the scope for sustainable intensification.

But the two other cases of rainy season sorghum in Maharashtra and rainy season pearl millet in Maharashtra present the evidence in the opposite direction. They are neither productive nor profitable when compared with the competing crops or cropping systems. Being cereal crops, they do not contribute to the sustainability indicators like water-use efficiency, nitrogen-use efficiency, nitrogen-phosphorus ratio, organic carbon dynamics etc. The evidence with respect to other sustainability indicators like fodder availability and food security is mixed. No wonder, these crops are fast losing area shares in all the important districts of Maharashtra growing them. The future trends may not be different from the declining trends observed in the past. Unless the research system comes up with more sustainable cropping systems, the fortunes of rainy season sorghum and rainy season pearl millet may not be reversed in the near future. The perceptions of the sample farmers also endorsed that the sustainability indicators are showing declining trends in the case of rainy season sorghum, while they were mixed in case of rainy season pearl millet. These two cases in Maharashtra do not indicate any scope for their sustainable intensification. While policy distortions had their own share in reducing the profitability of sorghum and pearl millet, the process of change cannot be reversed even if policy makers are sincere in correcting the policy bias against these coarse cereals.

The methodology of assessing the sustainable intensification is still evolving and the approaches used in the present study have scope for further development and application in varied cropping systems in the semi-arid tropics region. Some additional indicators can be developed and employed and more innovative definitions and approaches can be tried in the future.

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Appendix -1

List of variables used in the analysis

Sl.no	Variable name	Method of estimation	Source of data
1	Crop yield	Crop simulation model	30 years simulated data
2	Water-use efficiency (WUE)	Crop simulations model	30 years simulated data
3	Total organic carbon at maturity (OCTAM)	Crop simulations model	30 years simulated data
4	Nitrogen-use efficiency (NUE)	Crop simulations model	30 years simulated data
5	Nitrogen fixed during crop season (NFXM)	Crop simulations model	30 years simulated data
6	Nitrogen leached during crop season (NLCM)	Crop simulations model	30 years simulated data
7	Inorganic nitrogen at maturity (NIAM)	Crop simulations model	30 years simulated data
8	Crop nitrogen uptake (CNAM)	Crop simulations model	30 years simulated data
9	Return over variable cost (ROVC)	Cost concepts	Primary data
10	Fodder availability per acre	Household survey	Primary data
11	Share of ROVC in total household food expenditure	Household survey	Primary data
12	N/P ratio	Household survey	Primary data
13	Share of household cereal consumption to total food production	Household survey	Primary data
14	Returns to scale	Cobb-Douglas production function	Primary data
15	Technical efficiency of inputs	Stochastic frontier production function	Primary data
16	Drivers of sustainability	Principal Components Analysis (PCA)	Primary data
17	Crop diversification index	Simpson index	Primary data
18	Network index	Cumulative scale	Primary data
19	Age	Household survey	Primary data
20	Education	Household survey	Primary data

List of indicators used for assessing the perceptions on household sustainability	
Indicator	Source of data
Livestock population (No. per Hh)	Primary data
Availability of fodder/grazing pastures	Primary data
Area under green manure crops	Primary data
Land allocation for food crops (acres)	Primary data
Average land holding size of farm (acres)	Primary data
Land-use intensity (no. of crops per year)	Primary data
Use of legumes in crop-rotations /inter-cropping	Primary data
FYM/other organic matter application rate (qtl/acre/year)	Primary data
Soil and water conservation investments per acre (private and public)	Primary data
Soil loss due to erosion	Primary data
Soil fertility status (organic carbon and NPK levels)	Primary data
In-organic fertilizers (N, P, K – application rate)	Primary data
Micro-nutrient application (kg/acre)	Primary data
Frequency of soil testing and use of fertilizers based on recommendations	Primary data
Expenditure on plant protection chemicals (Rs/acre)	Primary data
Expenditure on farm mechanization (Rs/acre)	Primary data

Appendix -2

Case 1: Chickpea in Andhra Pradesh

Time series data on area, production and yield were obtained from FAOSTAT and relevant Government of India and State of Andhra Pradesh offices. State (sub-national) and district data were collected to examine the spatial distribution of crop production across India. More detailed sub-district (*mandal*) distribution available for the whole state of Andhra Pradesh was used as the basis for constructing the primary level sampling frame for the study. The systematic collection of available census village/household data was followed to construct the secondary and tertiary sampling frame for the study. For example, it was most useful to be guided by the spatial GIS map (see Figure A1) drawn using the mandal level data available.

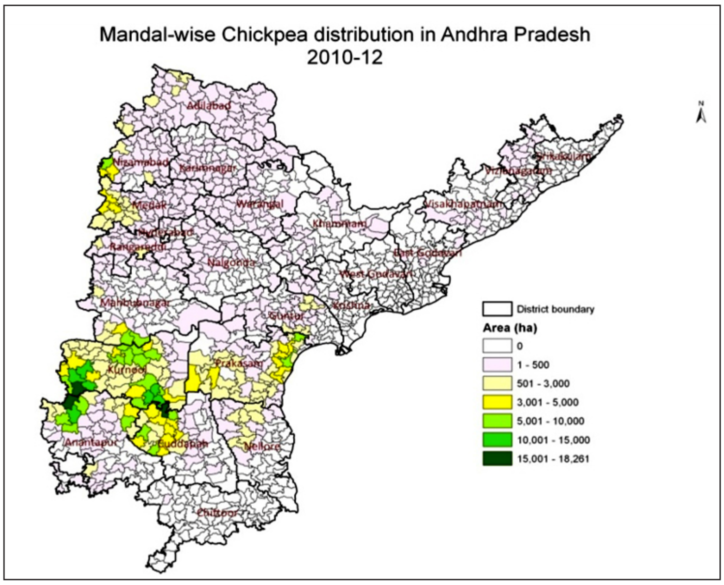


Figure A1. Spatial distribution of area grown to chickpea by mandal in united AP, 2010-12.

Out of the 281 chickpea growing mandals in seven districts, mandals with a chickpea area more than 3000 ha were initially considered for the study (i e, nearly 61 mandals). The details on the sampling scheme (specifying the number of sample mandals, sample villages and sample households) are presented in Table A1. A sample of nine chickpea growers were randomly selected and interviewed with a structured questionnaire. The study collected information that pertained to the 2011-12 cropping season. Overall, a total of 810 households were covered from 90 villages and 30 mandals in seven districts of Andhra Pradesh representing more than 71% of the chickpea area in the state. The details of the final sample mandals selected for the study are summarized in Table A2.

Trends in growth of area and production of chickpea in Andhra Pradesh

During the past two decades, chickpea made rapid strides in both area and production in Andhra Pradesh. Area under chickpea increased at a compound growth rate of 12.40% during the last decade of the twentieth century and by 8.90% during the first decade of the twenty first century (Table A3). Production of chickpea increased even faster than the area under cultivation due to an increase in productivity. Production of chickpea increased at the rate of 15.63% per annum during 1991-2000 and by 11.40%

Table A1. Primary, secondary and tertiary samples based on the sampling frame constructed.

District	No. of mandals growing chickpea	Mandals with chickpea area > 3000 ha	No. of mandals selected for the study	No. of villages covered in the study
Kurnool	53	23	13	39
Prakasam	50	10	4	12
Anantapur	42	7	5	15
Kadapa	30	12	5	15
Medak	45	3	1	3
Nizamabad	30	3	1	3
Mahabubnagar	31	3	1	3
Andhra Pradesh	281	61	30	90

Table A2. Final sample of mandals for the chickpea survey.

Sl.no.	District	Mandal	Sl.no.	District	Mandal
1	Anantapur	Kanekal	16	Kurnool	Dornipadu
2	Anantapur	Vidapanakal	17	Kurnool	Sanjamala
3	Anantapur	Tadpatri	18	Kurnool	Uyyalawada
4	Anantapur	Uravakonda	19	Kadapa	Mylavaram
5	Anantapur	Beluguppa	20	Kadapa	Peddamudium
6	Kurnool	Gudur	21	Kadapa	Rajupalem
7	Kurnool	Kurnool	22	Kadapa	Simhadripuram
8	Kurnool	Midthur	23	Kadapa	Veerapunayunipalle
9	Kurnool	Adoni	24	Prakasam	Parchur
10	Kurnool	Alur	25	Prakasam	Janakavarampanguluru
11	Kurnool	Aspari	26	Prakasam	Naguluppalapadu
12	Kurnool	Banaganapalle	27	Prakasam	Ongole
13	Kurnool	Chippagiri	28	Mahabubnagar	Manopad
14	Kurnool	Maddikera (East)	29	Medak	Manoor
15	Kurnool	Koilkuntla	30	Nizamabad	Madnoor

during 2001-2010. Among the districts, Prakasam registered a phenomenal growth of 24.75% in area during 1991-2000. It was followed by Kadapa, Anantapur and Kurnool in terms of double digit area growth during 1991-2000. Among the Telangana districts, Adilabad, Mahabubnagar, Medak and Rangareddy registered single digit area growth. But Karimnagar, Nizamabad, Nalgonda and Guntur districts reported negative growth rates in area in this decade. However, all the five districts in Andhra and two districts in Telangana for which data were available recorded positive growth rates in production.

But, in the next decade, all the seven districts in Telangana and six districts in Andhra reported positive growth rates in chickpea area. Highest growth rates (double digit and positive) in area were reported from Nellore, Nizamabad, Adilabad and Mahabubnagar districts. The remaining districts reported relatively lower growth rates (positive but single digit) in chickpea area. The maximum growth rate of 38% in production was reported by Nizamabad district and it was followed by Nellore, Adilabad, Mahabubnagar, Anantapur and Kurnool districts. The remaining districts of Guntur, Kadapa, Prakasam, Medak and Rangareddy recorded positive but single digit growth rates. Such high growth rates in both area and production both at the state level as well as at the district level illustrate the fact that chickpea crop has gained considerable importance in the state because of its relative profitability *vis*-a-*vis* the other competing crops during the postrainy season.

Table A4 presented the *quinquennial* average area data from 1966 to 2010 in different districts of Andhra Pradesh state. In 1966-70, Medak, Guntur and Hyderabad (Rangareddy) were the important districts for chickpea cultivation in the state. The area under chickpea in the state declined between 1966-70 and 1981-85. But the lost area was regained between 1981-85 and 1991-95. There was a rapid increase in the area under chickpea in the state between 1991-95 and 2006-10, registering a more than six fold growth in a matter of two decades. Kurnool, Prakasam, Anantapur and Kadapa districts emerged as the important chickpea growing districts in the state. Medak, Nizamabad and Mahabubnagar occupied the fifth, sixth and seventh positions with respect to area under chickpea cultivation.

Table A3. District-wise historical trends of chickpea in united Andhra Pradesh.

	Area growth rate (%)		Production growth rate (%)	
District	1991-2000	2001-2010	1991-2000	2001-2010
Adilabad	8.36	17.06	-	20.44
Nizamabad	-4.46	30.17	-	38.81
Karimnagar	-6.03	0.55	-	-2.06
Medak	5.98	4.99	2.08	4.99
Rangareddy	4.30	3.26	11.59	4.16
Mahabubnagar	7.58	14.50	-	20.30
Nalgonda	-4.39	-	-	-
Warangal	-	2.26	-	-1.64
Guntur	-3.74	8.65	6.45	8.90
Prakasam	24.75	5.76	31.63	5.90
Nellore	-	31.13	-	25.16
Kadapa	21.65	7.47	20.57	6.03
Kurnool	12.17	9.53	5.74	13.61
Anantapur	18.47	8.79	17.46	18.87
Total AP	12.40	8.90	15.63	11.40

Table A4. Area grown to chickpea from 1966 to 2011 in united Andhra Pradesh ('000 ha).

District	1966-70	1971-75	1976-80	1981-85	1986-90	1991-95	1996-2000	2001-05	2006-10	2009-11
Kurnool	6	5	6	6	15	35	54	128	227	228
Prakasam	1	1	1	1	3	8	18	70	94	84
Anantapur	2	2	2	3	7	16	26	49	84	94
Kadapa	1	1	1	1	3	7	18	42	71	73
Medak	18	16	15	13	12	15	19	31	38	40
Nizamabad	13	12	9	6	4	4	3	6	24	25
Mahabubnagar	5	4	3	3	2	3	3	11	23	28
Adilabad	5	5	4	3	2	2	3	6	17	11
Guntur	8	5	5	5	3	2	1	8	12	9
Nellore	0	0	0	0	1	0	0	2	11	10
Karimnagar	5	5	3	2	1	1	1	4	3	3
Warangal	2	2	2	1	1	1	1	2	2	2
Krishna	1	1	1	0	0	0	0	0	1	1
Nalgonda	2	2	2	1	0	1	1	0	1	1
East Godavari	1	1	0	0	0	0	0	0	0	0
Visakhapatnam	0	0	0	0	0	0	0	0	0	0
Khammam	1	1	1	1	0	0	0	0	0	0
Srikakulam	0	0	0	0	0	0	0	0	0	0
Chittoor	0	0	0	0	0	0	0	0	0	0
Hyderabad	8	8	7	5	3	0	0	0	0	0
West Godavari	0	0	0	0	0	0	0	0	0	0
Total	80	71	62	52	59	95	147	361	607	609

Assessing chickpea sustainability using crop simulation models

Table A5. Sustainability of different cropping systems in Prakasam district.

Parameter	Fallow-chickpea	Fallow-fallow	Fallow-maize (Equivalent yield to Chickpea)
Yield	3662	0.0	1912
WUE	7.4	0.0	3.5
NUE	183.1	0.0	0.2
NFXM	136.4	0.0	0.0
NLCM	46.9	1.2	3.8
NIAM	85.5	3.1	1.2
CNAM	168.5	0.0	1.4
OCTAM	133	1.2	1.3

Yield: kg/ha; WUE: Water-use efficiency (kg/ha mm); NUE: Nitrogen-use efficiency kg grain/kg N applied; NFXM: Nitrogen fixed during crop season (kg/ha); NLCM: Nitrogen leached during crop season (kg/ha); NIAM: Inorganic nitrogen at maturity (kg/ha); CNAM: crop nitrogen uptake (kg/ha) and OCTAM: Total organic carbon at maturity stage (tons/ha)

Table A6. Sustainability of different cropping systems in Kurnool district.

Parameter	Fallow-chickpea	Fallow-fallow	Fallow-sorghum (Equivalent yield to Chickpea)
Yield	2610	0.0	712
WUE	5.9	0.0	5.9
NUE	130.5	0.0	8.9
NFXM	91.7	0.0	0.0
NLCM	7.7	5.1	1.1
NIAM	111.1	33.7	20.3
CNAM	127.9	0.0	6.8
OCTAM	134	11.6	12.3

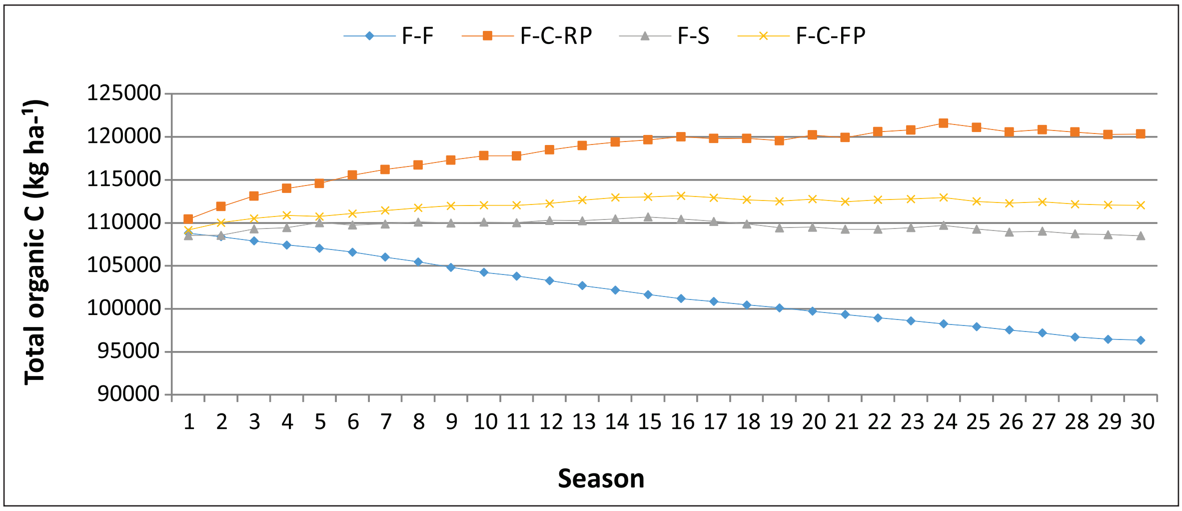
Table A7. Sustainability of different cropping systems in Kadapa district.

Parameter	Fallow-chickpea	Fallow-fallow	Fallow-sorghum (Equivalent yield to Chickpea
Yield	2961	0.0	774
WUE	6.3	0.0	4.9
NUE	148.1	0.0	9.7
NFXM	79.3	0.0	0.0
NLCM	10.1	1.1	2.5
NIAM	113.8	6.75	30.7
CNAM	144.3	0.0	7.3
OCTAM	134.1	11.6	12.3

Table A8. Sustainability of different cropping systems in Anantapur district.

Parameter	Fallow-chickpea	Fallow-fallow	Fallow-sorghum (Equivalent yield to CP)
Yield	1928	0.0	806
WUE	4.3	0.0	3.9
NUE	96.4	0.0	10.1
NFXM	66.2	0.0	0.0
NLCM	8.6	1.0	0.8
NIAM	62.3	6.3	11.4
CNAM	111.4	0.0	8.9
OCTAM	118.3	10.2	10.9

Simulated soil carbon dynamics of chickpea system over the last thirty seasons



F-F: Fallow –Fallow; F-C-RP: Fallow-Chickpea (Improved practice); F-S: Fallow-Sorghum; F-C-FP: Fallow-Chickpea (farmer practice)

Figure A2. Carbon sequestration across cropping systems in Anantapur.

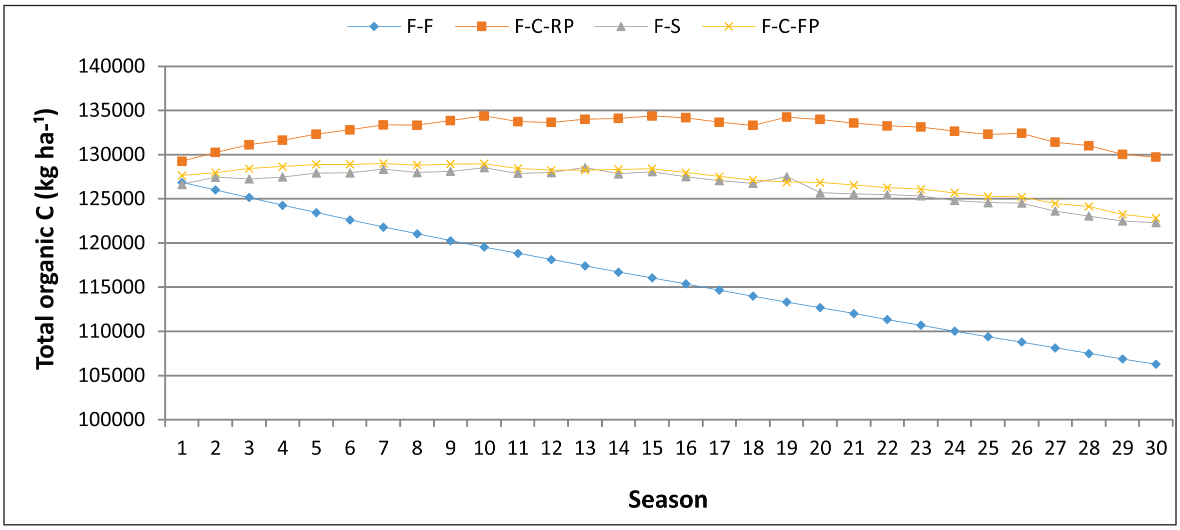


Figure A3. Carbon sequestration across cropping systems in Prakasam.

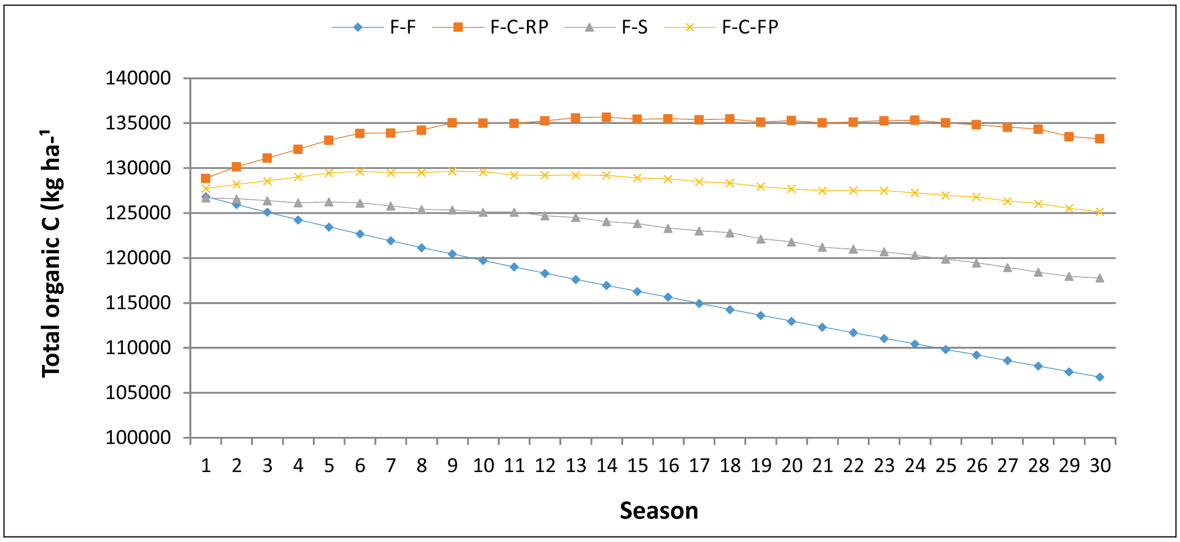


Figure A4. Carbon sequestration across cropping systems in Kurnool.

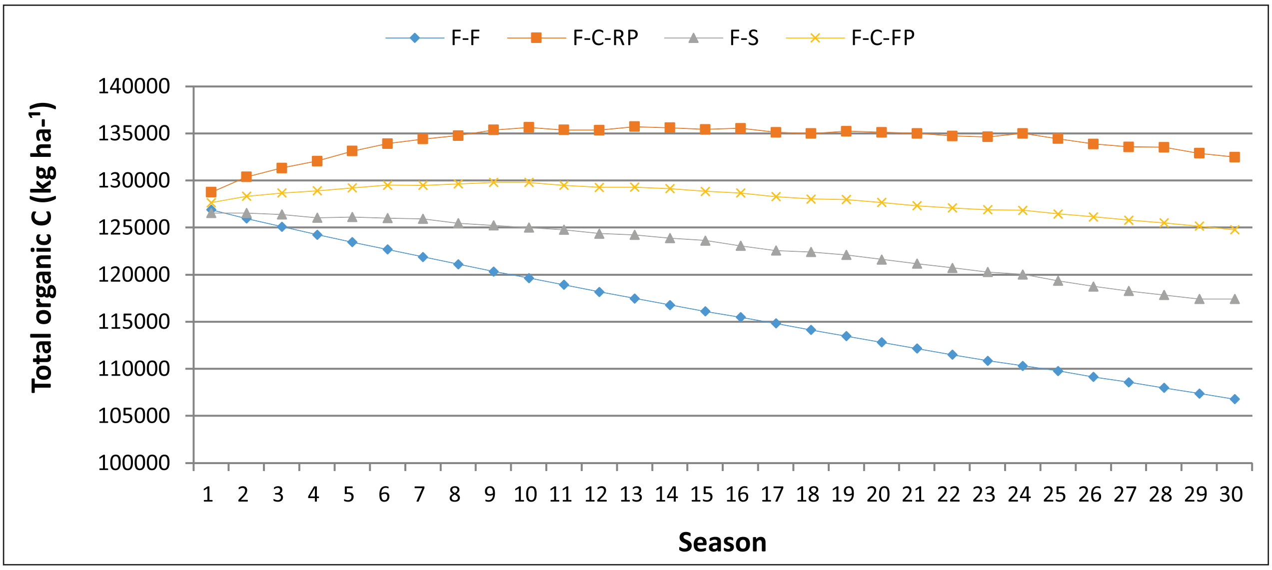


Figure A5. Carbon sequestration across cropping systems in Kadapa district.

Resource-use efficiency and returns to scale

Table A9. Resource-use efficiency in chickpea (JG 11) cultivation.

	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
Variables	B	Std. Error	Beta		
(Constant)	4.148	1.676		2.474	.014
Area	.532*	.207	.415	2.572	.011
Labor cost	.514*	.131	.354	3.913	.000
Bullock cost	-.015	.011	-.048	-1.360	.175
Machinery cost	.310*	.092	.265	3.375	.001
Seed cost	-.250	.157	-.198	-1.594	.113
Manure cost	-.008	.007	-.038	-1.187	.237
Fertilizer cost	.169***	.092	.141	1.832	.069
Pesticide cost	-.036	.058	-.031	-.617	.538

n = 201, R^2 = 0.84, F static = 124.93* *: sig at 1%; **: sig at 5%; ***: sig at 10%

Table A10. Resource-use efficiency in chickpea (Vihar/KAK2) cultivation.

	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
Variables	B	Std. Error	Beta		
(Constant)	6.00	1.28		4.70	0.00
Area	0.49*	0.14	0.47	3.36	0.00
Labor cost	0.00	0.13	0.00	0.03	0.98
Bullock cost	0.01***	0.01	0.07	1.73	0.09
Machinery cost	0.28*	0.09	0.26	3.04	0.00
Seed cost	0.37*	0.12	0.35	2.98	0.00
Manure cost	-0.02**	0.01	-0.05	-2.05	0.04
Fertilizer cost	-0.10**	0.05	-0.11	-2.00	0.05
Pesticide cost	-0.02	0.04	-0.02	-0.45	0.66

n = 65, R^2 = 0.97, F static = 202.2* *: sig at 1%; **: sig at 5%; *** sig at 10%

Table A11. Resource-use efficiency in sorghum cultivation.

Variables	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
	B	Std. Error	Beta		
(Constant)	5.94	1.91		3.11	0.00
Area	0.58**	0.23	0.44	2.50	0.02
Labor cost	0.28	0.20	0.19	1.44	0.16
Bullock cost	-0.02	0.03	-0.04	-0.47	0.64
Machinery cost	0.08	0.12	0.08	0.68	0.50
Seed cost	0.05	0.11	0.05	0.45	0.65
Manure cost	-0.01	0.02	-0.04	-0.44	0.66
Fertilizer cost	0.06	0.06	0.11	1.00	0.32
Pesticide cost	0.00	0.02	-0.01	-0.16	0.87
Irrigation	0.07*	0.02	0.32	3.37	0.00

n = 52, R^2 = 0.81, F static = 19.85* *: sig at 1%; **: sig at 5%; *** sig at 10%

Table A12. Stochastic Frontier Production function for estimating inefficiencies.

Variable	Coefficient	Standard error	t-ratio
beta 0	5.23	1.44	3.63
Area	0.54*	0.17	3.17
Labor cost	0.34*	0.15	2.29
Bullock cost	0.01	0.01	1.51
Machinery Cost	0.22*	0.09	2.49
Seed cost	-0.07	0.12	-0.55
Manure cost	-0.02*	0.01	-3.34
Fertilizer cost	0.15**	0.09	1.71
Pesticide cost	-0.01	0.06	-0.10
delta 0	1.18	0.32	3.68
Age	0.00	0.00	0.96
Prakasam	-1.53*	0.39	-3.95
Kurnool	-0.41*	0.13	-3.12
Kadapa	-0.35*	0.15	-2.38
Uneducated	-0.27*	0.13	-2.15
CDI	0.11	0.27	0.40
NWI	-0.56	0.53	-1.05
Sigma-square	0.16	0.03	5.34
gamma	0.97	0.03	28.99

Log likelihood ratio 0.67 *: Sig at 1% level; **: Sig at 5% level

Case-2 Rainy season Sorghum in Maharashtra

The twenty tehsils were selected using robust sampling framework for Maharashtra state to conduct representative household survey (see Table A13). Three tehsils each which have the highest area under rainy season sorghum were selected from Nanded and Latur districts. Jalgaon, Parbhani and Osmanabad, with medium concentration of rainy season sorghum area are represented by two tehsils each. The remaining eight districts with relatively less area under rainy season sorghum are represented in the sample by one tehsils each. The sample districts, tehsils and villages selected for the survey are shown in Figure A6.

Three villages from each selected tehsil and thus a total of sixty villages were chosen for the primary survey. Six rainy season sorghum growers were identified randomly from each selected village. So, a total of 360 farmers were interviewed from 60 villages and 20 tehsils in the state.

Table A13. Tehsils selected for the sample from different districts.

S. No.	District	Tehsils	S. No.	District	Tehsils
1	Akola	Patur	11	Nanded	Bhokar
2	Amravati	Daryapur	12	Nanded	Hadgaon
3	Beed	Kaij	13	Nanded	Mukhed
4	Dhule	Shirpur	14	Parbhani	Sonpeth
5	Hingoli	Aundha	15	Parbhani	Parbhani
6	Jalgaon	Muktainagar	16	Sangali	Khanapur
7	Jalgaon	Rawer	17	Satara	Karad
8	Latur	Devani	18	Osmanabad	Umerga
9	Latur	Latur	19	Osmanabad	Kalamb
10	Latur	Nilanga	20	Yavatmal	Pusad

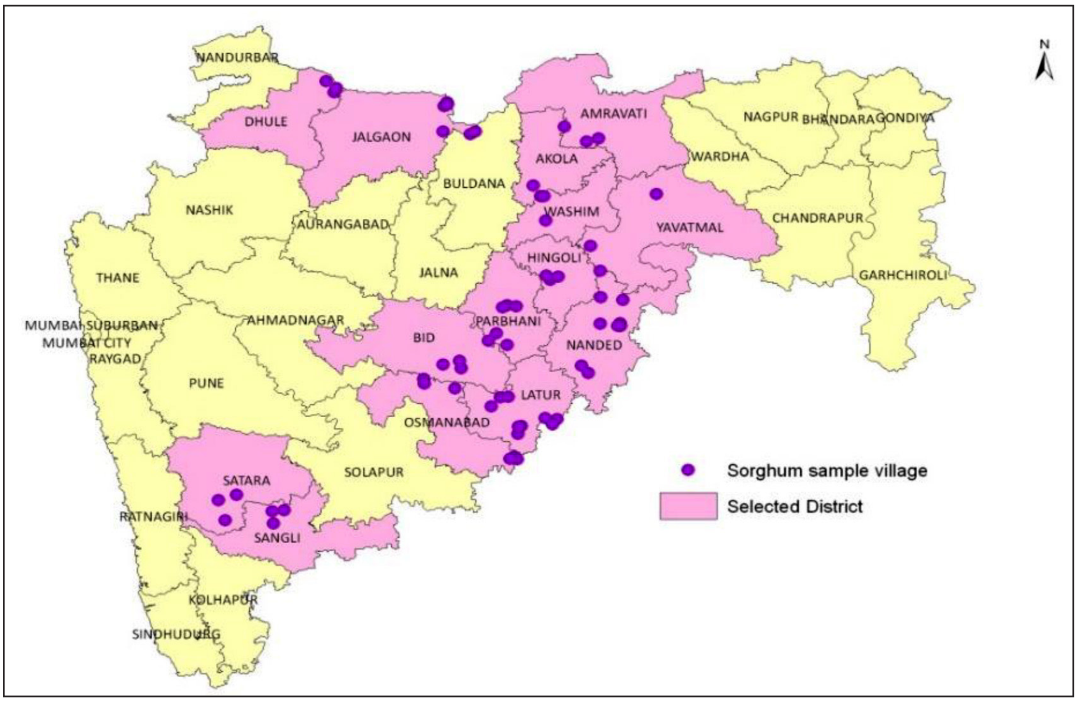


Figure A6. Selection of districts and villages for primary survey in Maharashtra.

Soil carbon simulations

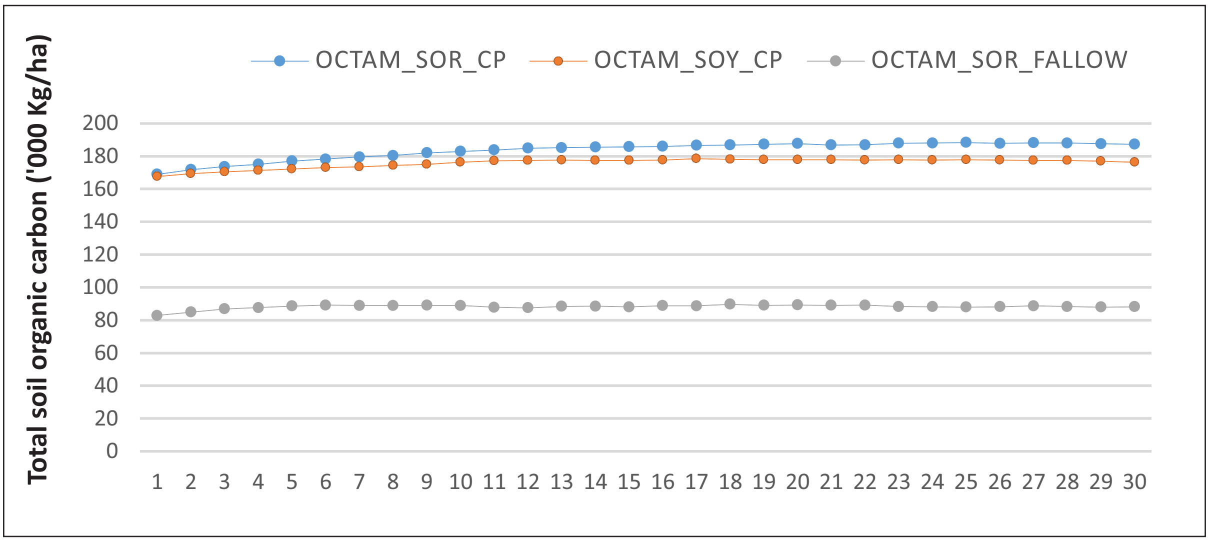


Figure A7. Simulated soil carbon dynamics over the last thirty seasons at Parbhani.

Resource-use efficiency

Table A14. Resource-use efficiency of sorghum cultivation in Maharashtra.

	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
Variables	B	Std. Error	Beta		
(Constant)	.454	1.366		.333	.740
Area	.105**	.052	.156	2.007	.048
Labor cost	.447*	.096	.413	4.663	.000
Bullock cost	.243*	.051	.406	4.721	.000
Manure cost	.021***	.011	.133	1.828	.071
Machinery cost	.213*	.056	.342	3.777	.000
Seed cost	.323	.196	.117	1.648	.103
Fertilizer cost	-.001	.014	-.008	-.104	.917
Pesticide cost	.023**	.010	.157	2.199	.030

n =106 , R^2 = 0.53, F static = 13.3* *: sig at 1%; **: sig at 5%; ***: sig at 10%

Table A15. Resource-use efficiency of soybean cultivation in Maharashtra.

	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
Variables	B	Std. Error	Beta		
(Constant)	6.869	1.603		4.285	.000
Area	.643*	.211	.557	3.049	.003
Labor cost	.089	.112	.071	.795	.430
Bullock cost	-.072	.053	-.072	-1.338	.186
Manure cost	.006	.008	.038	.851	.398
Seed cost	.450*	.210	.398	2.137	.037
Fertilizer cost	-.060	.071	-.056	-.849	.399
Pesticide cost	.022***	.013	.071	1.647	.105

n = 69, R^2 = 0.89, F static = 78.01* *: sig at 1%; **: sig at 5%; ***: sig at 10%

Table A16. Resource-use efficiency of chickpea cultivation in Maharashtra.

Variables	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
	B	Std. Error	Beta		
(Constant)	4.21	1.42*	2.96	2.97	0.00
Area	0.73	0.24*	3.04	3.09	0.00
Labor cost	0.44	0.23**	1.91	1.94	0.05
Bullock cost	-0.07	0.13	-0.54	-0.54	0.58
Seed cost	0.28	0.15***	1.86	1.84	0.07
Fertilizer cost	-0.14	0.16	-0.87	-0.88	0.37
Pesticide cost	-0.00	0.03	-0.03	-0.06	0.95

n = 56, R^2 = 0.85, F static = 54.01* *: sig at 1%; **: sig at 5%; ***: sig at 10%

Estimation of inefficiencies in sorghum cultivation

Table A17. Stochastic Frontier Production function for estimating inefficiencies.

Variable	coefficient	Standard error	t-ratio
beta 0	2.59	0.99	2.62
Area	0.08	0.16	0.51
Labor cost	0.29*	0.11	2.60
Bullock cost	0.06	0.06	0.95
Manure cost	-0.02*	0.01	-2.18
Machinery cost	0.32*	0.06	5.66
Seed cost	0.33*	0.16	2.04
Fertilizer cost	-0.05*	0.02	-2.36
Plant protection cost	0.02	0.01	1.52
delta 0	-0.30	0.11	-2.66
Age	0.00	0.00	1.12
CDI	0.16	0.22	0.74
NWI	0.45**	0.26	1.74
Marathwada	0.03	0.08	0.40
WMH	-0.02	0.08	-0.22
Education	0.11	0.09	1.30
sigma-square	0.12	0.01	9.28
Gamma	0.00	0.01	0.05

Log likelihood=0.62 * Significance at 1% level ** Significance at 5% level

Case-3: Pearl millet in Maharashtra

The sample for the study covered 360 households from 60 villages and 20 tehsils in 9 districts of Maharashtra state (see Table A18). The selected sample villages and districts across Maharashtra are also depicted in Figure A8.

Table A18. Primary sample of mandals in pearl millet survey.

S.no	District	Mandal	S.no	District	Mandal
1	Ahmednagar	Sangamner	11	Dhule	Sindkheda
2	Ahmednagar	Pathardi	12	Jalgaon	Parola
3	Ahmednagar	Shevgaon	13	Nashik	Malegaon
4	Ahmednagar	Rahuri	14	Nashik	Sinnar
5	Aurangabad	Aurangabad	15	Nashik	Baglan (Satana)
6	Aurangabad	Gangapur	16	Nashik	Chandwad
7	Beed	Patoda	17	Pune	Shirur
8	Beed	Majalgaon	18	Pune	Purandhar
9	Beed	Parali	19	Sangali	K.Mahankaal
10	Dhule	Sakri	20	Satara	Man

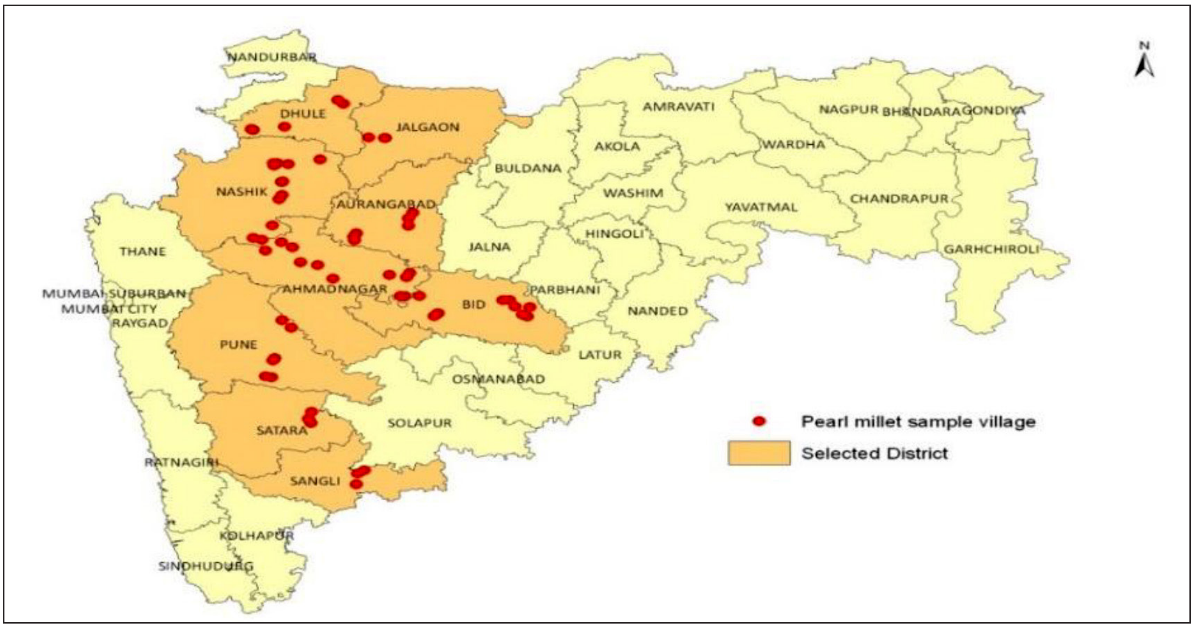


Figure A8. Selection of districts and villages for primary survey in Maharashtra, 2012.

Table A19. Resource-use efficiency in pearl millet cultivation.

	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
Variables	B	Std. Error	Beta		
(Constant)	-.924	1.738		-.531	.596
Area	.034	.099	.026	.344	.731
Labor cost	.586*	.154	.314	3.809	.000
Bullock cost	.033***	.019	.122	1.736	.085
Machinery cost	.580*	.092	.454	6.281	.000
Manure cost	-.010	.015	-.043	-.687	.493
Seed cost	.038	.232	.010	.162	.872
Fertilizer cost	.085***	.049	.122	1.737	.084

n =167 , R^2 = 0.41, F static = 15.9*   *: sig at 1%; **: sig at 5%; ***: sig at 10%

Table A20. Resource-use efficiency in cotton cultivation.

	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
Variables	B	Std. Error	Beta		
(Constant)	-4.867	2.547		-1.911	.062
Area	.194	.120	.190	1.616	.113
Labor cost	1.379*	.272	.718	5.060	.000
Bullock cost	-.119*	.041	-.300	-2.869	.006
Machinery cost	.149	.181	.091	.825	.414
Manure cost	.005	.020	.025	.261	.795
Seed cost	.518**	.242	.219	2.144	.037
Fertilizer cost	-.235	.164	-.157	-1.431	.159
Pesticide cost	.056**	.029	.209	1.953	.057

n =55 , R^2 = 0.62, F static = 9.4*   *: sig at 1%; **: sig at 5%

Table A21. Resource-use efficiency in maize cultivation.

	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
Variables	B	Std. Error	Beta		
(Constant)	-5.354	3.464		-1.545	.133
Area	.013	.145	.013	.089	.929
Labor cost	.147	.314	.100	.467	.644
Bullock cost	.098*	.032	.694	3.068	.005
Machinery cost	1.267*	.226	1.323	5.608	.000
Manure cost	.011	.015	.102	.732	.470
Seed cost	.378***	.215	.279	1.760	.089
Fertilizer cost	.146	.116	.218	1.258	.218
Irrigation cost	-.066*	.022	-.633	-3.037	.005

n =39 , R^2 = 0.61, F static = 5.9*   *: sig at 1%; **: sig at 5%

Table A22. Stochastic frontier production function for estimating inefficiencies.

Variable	Coefficient	Standard error	t-ratio
beta 0	3.00	1.26	2.38
Area under crop	0.28	0.21	1.35
Labor	0.61*	0.11	5.49
Bullock	0.02	0.02	0.81
Machinery	0.35*	0.07	5.03
CP	-0.01	0.02	-0.52
Seed	-0.22	0.21	-1.04
Fertilizer	0.05	0.03	1.55
delta 0	-29.15	8.85	-3.29
Age	0.28	0.07	4.00
CDI	20.81*	6.14	3.39
NWI	8.31*	3.14	2.65
Region	3.80*	1.33	2.86
Educated	-11.72*	2.65	-4.42
sigma-s	25.24	6.72	3.75
gamma	1.00	0.00	93.95

Log likelihood = 0.20 * Significance at 1% level ** Significance at 5% level

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