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Seeking sustainable pathways for fostering agricultural
transformation in peninsular IndiaK H Anantha^{1,*}, Kaushal K Garg¹, Cameron A Petrie² and Sreenath Dixit¹¹ ICRISAT Development Centre, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Telangana 502 324, India² Department of Archaeology and McDonald Institute for Archaeological Research, University of Cambridge, Cambridge, United Kingdom

* Author to whom any correspondence should be addressed.

E-mail: k.anantha@cgiar.org**Keywords:** natural resource management intervention, best management practices, technology impact, sustainability, bridging yield gap, South Asia

Abstract

Sizable populations in developing countries in Asia and Africa live in dryland ecosystems, and agriculture in these areas faces major challenges including water scarcity, land degradation, poor infrastructure and insufficient access to markets. Natural resource management (NRM) interventions offer an important path to sustainable agricultural practices through increasing resource use efficiency, but true efficacy will only be achievable if these initiatives can be scaled up. This paper explores the impact of farm-scale NRM interventions undertaken in the state of Karnataka, India, between 2005 and 2020. NRM technologies such as soil health management, resource use efficiency and improved crop cultivars were demonstrated in more than 50 000 farmers' fields. Participatory demonstrations and capacity building initiatives were effectively used to co-create innovations for rapid and wide dissemination, and NRM practices involving the soil-nutrient-crop-water continuum were the subject of large-scale demonstrations. The demonstration fields were divided into treated and control fields, and efforts were made to measure cost of cultivation, irrigation application and crop yield. The soil health management interventions helped to enhance crop yield by 10%–60% over the control plots. Technologies specific to resource conservation have helped to conserve soil moisture, reduce irrigation requirement by 50–300 mm and reduce the cost of cultivation by US\$ 150 ha⁻¹. Improved cereal, pulse and oil seed cultivars increased crop yield minimum by 15%. Although these results have a large variability, they consistently showed the effectiveness of integrating NRM practices with crop demonstrations. These results are ideal for sensitizing stakeholders and policymakers to the benefits of adopting science-based approaches to NRM interventions in order to bridge yield gaps and address land degradation, food insecurity and poverty in dryland regions in South Asia and globally.

1. Introduction

Agriculture is the major source of livelihood for about 70% of rural people in the developing countries of Asia and Africa (Mashnik *et al* 2017). About 60%–80% of agricultural lands in these areas belongs to the dryland system, which faces a number of challenges such as degradation, water scarcity and poor agricultural productivity (de Araujo *et al* 2021). These regions are often coincident with abject poverty and malnutrition as there is often a direct relationship between socio-economic status and agricultural productivity (Hyman *et al* 2008,

Pandey *et al* 2016, Dhahri and Omri 2020). Climate change in recent years has further increased the uncertainty in resource availability and the risk of crop failure in drylands (Fleischer *et al* 2011, Acharyya 2014, Clay and Zimmerer 2020). There have been a number of improved technologies and innovations in agriculture systems, but these technologies have largely been focused on irrigated farming systems as it is more straightforward to transform agricultural systems with assured freshwater availability. Drylands have often been ignored due to various biophysical and socio-economic constraints (Pingali 2012, Kenneth and

Patricio 2013, Llewellyn 2018, Armanda *et al* 2019, Dinar *et al* 2019).

Numerous studies have revealed that there is a large yield gap in dryland systems (Rockstrom and Falkenmark 2015, Davis *et al* 2017, Kumar *et al* 2021). In general, dryland farming systems are considered as one-ton agriculture (i.e. 1000 kg ha⁻¹), which can be enhanced by 2–5 fold by introducing integrated natural resource management (NRM) interventions (Rockström *et al* 2010, Fischer 2015, Rao *et al* 2015, Fischer and Connor 2018) and it has been noted that they hold the big hope for addressing future food security (Patnaik and Narayanan 2015). A number of land, water, crop and agronomic management technologies have been specifically developed to decrease the yield gap of dryland systems in the last two decades. For example, various *in-situ* water harvesting interventions are helping to mitigate risks such as recurring droughts, long dry spells, and crop failures, and they building system resilience by enhancing moisture availability (Garg *et al* 2012, Singh 2015, Williams *et al* 2020). Adaptation strategies such as growing drought-tolerant, disease-resistant, and heat-tolerant crops (Rao *et al* 2019, Kumar *et al* 2021) are being pursued in order to deal with the impact of changing climate on livelihood vulnerability in the drylands (Senapati 2020). Impoverished soils, traditional cultivars, and moisture stress limit the realization of potential yield (Van Ittersum *et al* 2013, Rockstrom and Falkenmark 2015, Garg *et al* 2020a, 2020b). Thus, the integration of fertilizer application based on scientific soil testing, *in-situ* soil moisture conservation, improved crop cultivars, and crop management technologies (also called best management practices) can together have lasting effects and lead to resource optimization (Karlberg *et al* 2015, Liu *et al* 2017, Wani *et al* 2017). While these technologies have shown impacts on research farms or at pilot scale, they need to move beyond pilots to be scaled up to ensure that they can benefit more people over wider areas. There is lack of data availability which limits the understanding about the impact of various NRM interventions at farmers' fields especially in drylands of Asia and Africa that are facing similar challenges. This paper draws insights on reducing the current yield gap from a large scale project implemented between 2005 and 2020 in the state of Karnataka in southern peninsular India. Focus was given to intensive data collection on crop yields in response to large scale farm based NRM interventions that were widely implemented. The paper describes technology-specific impacts on the opportunity to bridge the yield gap along with enhancing resource use efficiency in dryland system. The findings of this study meet a number of the United Nations sustainable development goals (SDGs) for the dryland areas of Asia and Africa, and they are ideal for informing different stakeholders seeking to achieve sustainable crop intensification.

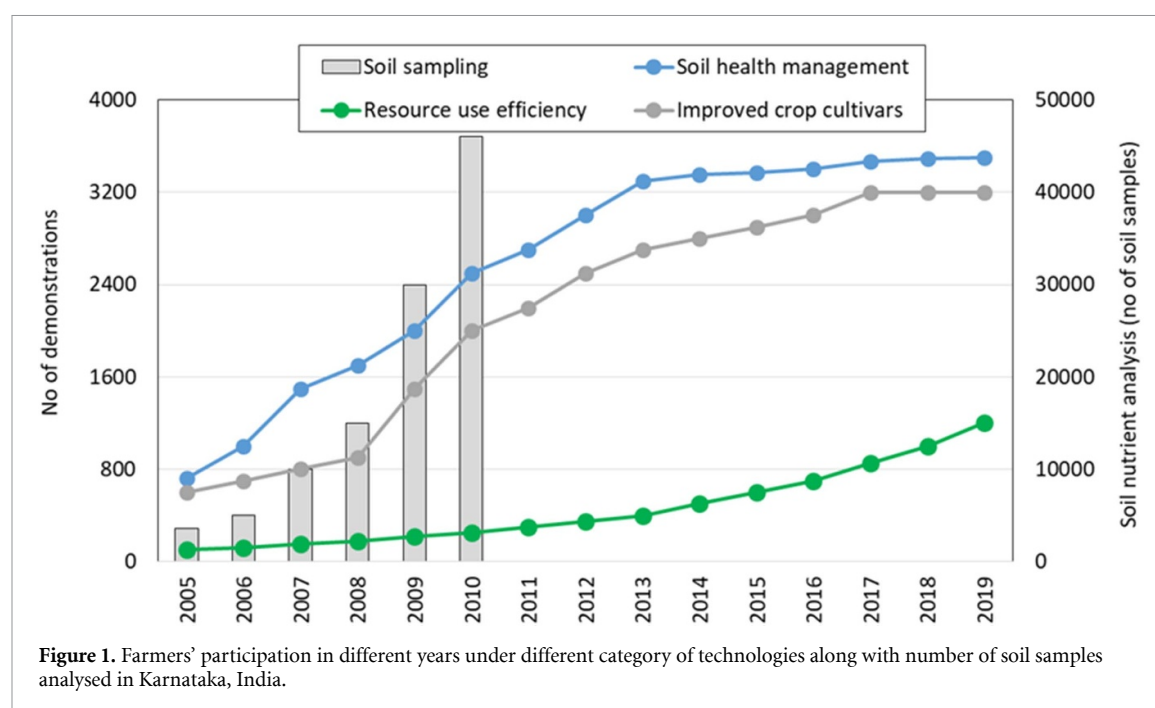
This paper describes key challenges of dryland areas in Karnataka state in southern India, which was experiencing stagnant agricultural growth. We show that a number of best management practices were suitable to address the above mentioned challenges in dryland systems. These interventions were focused on the three categories: soil health management; resource use efficiency; and improved crop cultivars. Their impact on crop yield was summarized through intensive data collection, and the compound effect of technologies on crop yield was further discussed to realize the potential of dryland systems with limited resource availability.

Our overarching aim was to evaluate the impacts of NRM interventions in tropical dryland agricultural systems. Specifically, we addressed three questions: (a) what is the baseline soil health in dryland agricultural systems? (b) how do yields change in response to three distinct large scale farm based interventions (i.e. soil health management, crop cultivar improvement, resource use efficiency improvements)? and (c) how does the combination of interventions alter yields?

2. Materials and methods

2.1. Study region

Karnataka state is located in southern peninsular India (11°30' N–18°30' N and 74° E–78°30' E) and occupies the second largest swathe of dryland area in the country, characterized by high variability in rainfall and topography, diverse soil types, land use, and cropping systems (Wani *et al* 2017). Rainfall ranges from 600 mm in the Northern Dry Zone to above 4000 mm in the Western Ghats and Coastal Humid Zone. A diverse cropping system is utilised in the state, comprising cereals, pulses, oilseeds, horticulture and other plantation crops. Among the important dryland crops grown are cereals such as finger millet and sorghum, oilseeds such as groundnut, soybean and sunflower, and pulses such as pigeonpea and chickpea (Patil *et al* 2014, Wani *et al* 2017). Paddy is an important cereal crop grown mostly under irrigated conditions and also in high rainfall regions. The yields for most of these crops grown in dryland conditions are between 300 and 2000 kg ha⁻¹. However, these areas have the potential to harvest the grain yield of 2000–5000 kg ha⁻¹ with improved management practices (IPs) under the same agroclimatic conditions (Singh 2015; FAO and DWFI 2015, Anderson *et al*, 2016, Wani *et al* 2017, Hajjarpoor *et al* 2018, Kumar *et al* 2021). Therefore, it was necessary to identify and demonstrate suitable technologies to bridge the yield gap in different cropping systems across different agro ecological regions of the state. With this realization, a consortium led by International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) with the support of Government of Karnataka has undertaken long term research and development initiative since 2005. The purpose of



this initiative was to identify suitable NRM technologies, demonstrate for large scale adoption and analyse its impact on crop yield, income and resource use efficiency.

2.2. Technology identification

Under this initiative, focus was place of identifying location and crop specific technologies that are available in research institutes, but have not yet reached farmers, as described below.

2.2.1. Soil health management

Nearly 110 000 soil samples from individual farmer's fields spread across more than 5000 villages in 30 districts were collected between 2005 and 2010 (figure 1). The samples were collected from the top soil layer (0–15 cm depth) with the help of trained extension workers. First, in each district, villages were identified based on the topo sequence (upland, midlands and low lands). About 15–25 soil samples were collected from each village representing major soil types. These samples were analyzed to identify deficiencies in micro (boron, zinc, iron, manganese, copper, molybdenum, chlorine), macro and secondary nutrients (phosphorous, potash, calcium, magnesium and sulfur) as well as levels of organic carbon (OC), soil pH and electrical conductivity. The soil critical limit for these nutrients is $P = 5 \text{ mg kg}^{-1}$, $K = 50 \text{ mg kg}^{-1}$, $B = 0.5 \text{ mg kg}^{-1}$, $Zn = 0.6 \text{ mg kg}^{-1}$, and $S = 10 \text{ mg kg}^{-1}$ (Sahrawat *et al* 2010). Based on the soil analysis, fertilizer recommendations were derived at sub-district level, and farmers were educated through participatory field technology demonstrations and capacity building initiatives. Under this recommendation, the full dose of a particular nutrient was only recommended if more than 50% of

farming fields were found deficient and half dose if less than 50% of the fields were found deficient in that particular nutrient (Sahrawat *et al* 2008, 2010).

2.2.2. Resource use efficiency

In-situ soil moisture conservation: various *in-situ* techniques that enhance residual soil moisture and reduce evaporation were demonstrated. A 1 m wide raised bed and 0.5 m furrow was laid out across the field slope so that crops could be grown on raised beds and intercultural operations could be performed using a furrow (Sharma *et al* 2019). The furrows aid the disposal of excess runoff during heavy rains (Pathak *et al* 2013). Similarly, other conservation technologies such as laser land leveling, use of a zero-till multi-crop planter (Jat *et al* 2019), and straw mulching were introduced.

Direct seeded rice (DSR) as a water saving technology. Paddy is one of the important staple crops grown in Karnataka especially in canal command areas, which is generally cultivated by transplanting method (transplanted rice (TPR)) under puddled condition, which requires a huge quantity (1500–2000 mm) of fresh water. An improved method of paddy cultivation called direct seeded rice (DSR) was demonstrated using seed drills in selected villages of Tumakuru, Raichur, Dharwad and Udupi districts of the state between 2012 and 2019. Here the crop is sown directly after the first monsoon rain combined with integrated weed management practices (Mishra *et al* 2017, Baghel *et al* 2020).

2.2.3. Improved crop cultivars

Improved crop cultivars developed by various research institutes and suitable for Karnataka state were demonstrated. These included major cereals

(paddy, maize, finger millet, pearl millet, sorghum); pulses (pigeonpea, green gram, black gram, chickpea); and oilseeds (groundnut, sunflower, soybean) crops.

2.3. Farmers' participatory technology demonstrations

The small and marginal farmers who hold less than 2 ha of land area were selected for technology demonstrations. These farmers were made aware of the benefits of technologies specific to their cropping system and encouraged to adopt them. After their consent, required inputs, machines, and management practices were made available with subsidized rates. Farmers undertook all the operations from beginning to harvest by investing their own funds. The farmers' fields were divided into two parts—a treated plot and a control plot. In the treated plot, the specific identified technology/intervention was demonstrated, whereas in control plot, farmers followed traditional practices to compare the impact of the tested technology in respective years. Since 2009, a single technology or a combination of two or three technologies (such as micronutrients, improved crop cultivars) was packaged with input subsidization (e.g. input cost reduction by 50%) to increase the rate of adoption across the state. About 2000–3500 farmers' participatory technology demonstrations were undertaken every year across the state between 2005 and 2020 (figure 1). About 20% of the fields were experimented for 3–4 years and 80% of fields were selected with different farmers every year such that a greater number of farmers were involved in participatory technology demonstrations. While undertaking technology demonstrations, intensive monitoring was ensured by deploying extension workers and field scientists that were responsible for technology dissemination (Wani *et al* 2017). This approach enabled the identification of the most promising and suitable technologies for large scale dissemination and sensitizing policymakers.

2.4. Data collection and analysis

Nearly 10 000 crop cutting studies (i.e. 20% of total demonstrations) were undertaken jointly by the Departments of Agriculture, Economics and Statistics, and scientists from University of Agricultural Sciences and ICRISAT in different crops to evaluate the impact of these measures. Data was collected on both farmers' practice (FP), the conventional method of cultivation, and IPs, which were the interventions mentioned in sections 2.2.1 to 2.2.3, by adopting a uniform crop sampling procedure in all the districts (Raju and Wani 2016). To assess the impact of the interventions on crop yield, crop cutting studies were undertaken by demarcating a 3 × 3 m area in three replications to cover the heterogeneity of the fields in about 20% of the demonstration fields from both treated and control plots between 2005 and 2020. In the crop cutting studies, the crop was harvested after the maturity from the demarcated area, air dried and grain weight was measured. The data from all the districts were compiled and statistical tests (ANOVA: analysis of variance) were performed to understand the level of significance in mean and its variance in the two datasets (FP and IP) for their respective technologies and crops. Further, post-hoc tests were performed to identify the significance among different treatment pairs (control vs. only cultivars; control vs. only management; control vs. both cultivars and management). Other monitoring parameters such as cost of cultivation (tillage operation, seed and fertilizer cost, energy cost, labour involved in sowing, irrigation application, interculture, harvesting) and amount of irrigation applied were also recorded for both treated and control plots.

Further, a response ratio (Yu *et al* 2018) was calculated for different crops under different rainfall conditions which indicates the proportionate change in crop yield in response to balanced fertilizer application compared to controlled condition using equation (1).

$$\text{Response ratio (-)} = \frac{\text{Crop yield of treated plot (kg ha}^{-1}\text{)}}{\text{Crop yield of control plot (kg ha}^{-1}\text{)}}. \quad (1)$$

To ascertain the impact of *in-situ* interventions, runoff gauges were installed at the outlets of selected landscapes with a 50–100 ha hydrological boundary in the districts of Kolar, Tumakuru, Vijayapura, Chikkamagaluru, Dharwad, Haveri and soil moisture was monitored at weekly intervals using the gravimetric method (World Bank 2009). In addition, rainfall data for respective districts was retrieved from the India Meteorological

Department on a daily time scale between 2005 and 2018. The data obtained from hydrological monitoring (runoff and soil moisture measurement) were used to understand the impact of *in-situ* interventions on moisture retention in treated fields (Garg *et al* 2020b). Further, rainfall vs. crop yield relationships were established for important crops such as finger millet, maize, groundnut and pigeonpea.

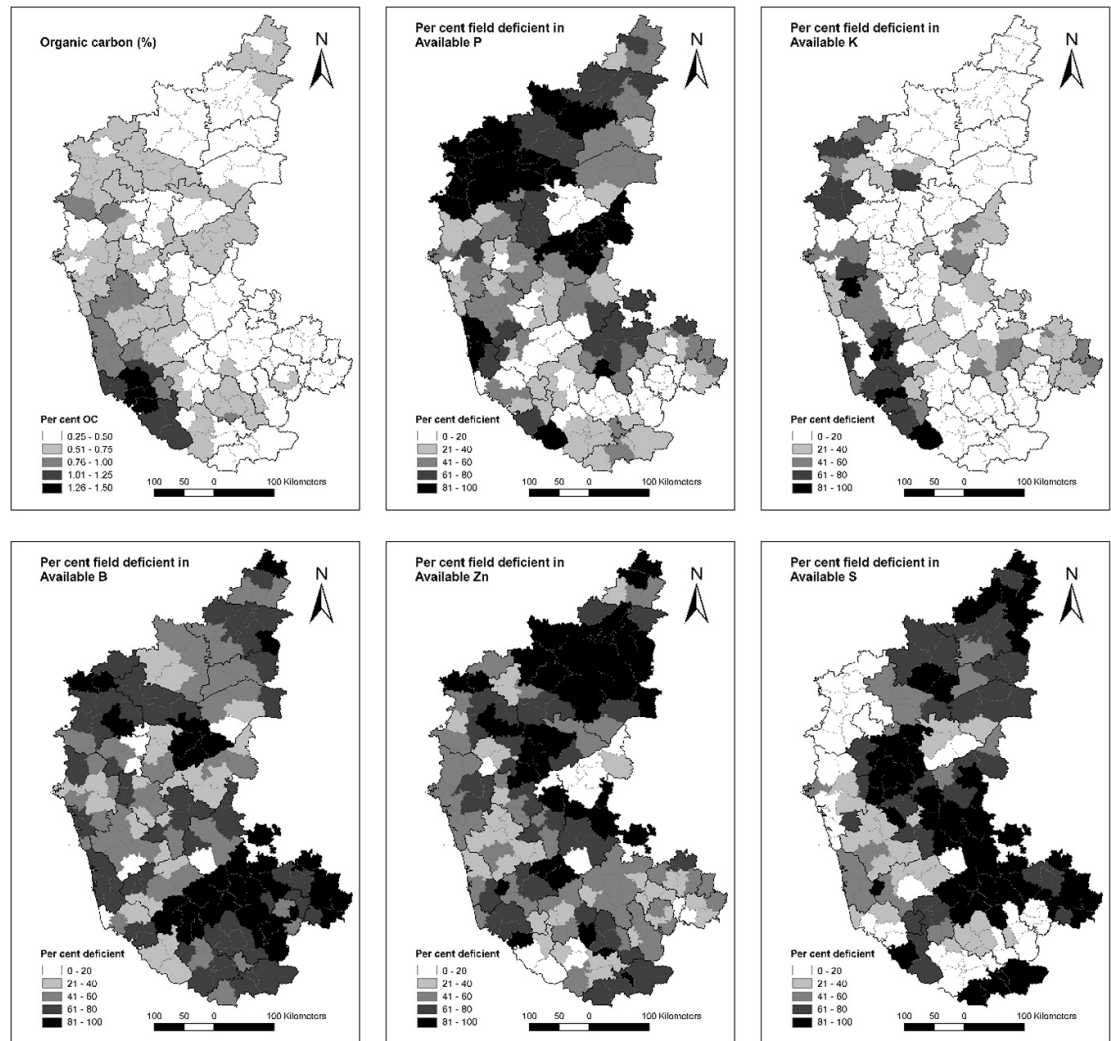


Figure 2. Percentage of fields deficient in OC, available P, available K, available B, available Zn and available S in 30 districts of Karnataka state.

In paddy fields, the water balance components (evapotranspiration, deep percolation) were analyzed using a one-dimensional simulation model called water impact calculator with inputs of rainfall, irrigation amount, soil retention properties and required crop specific details such as sowing date and length of crop period as discussed in Garg *et al* (2016) and Garg *et al* (2020a). Moreover, net income obtained from DSR (treated plot) and TPR (control plot) was calculated using equation (2).

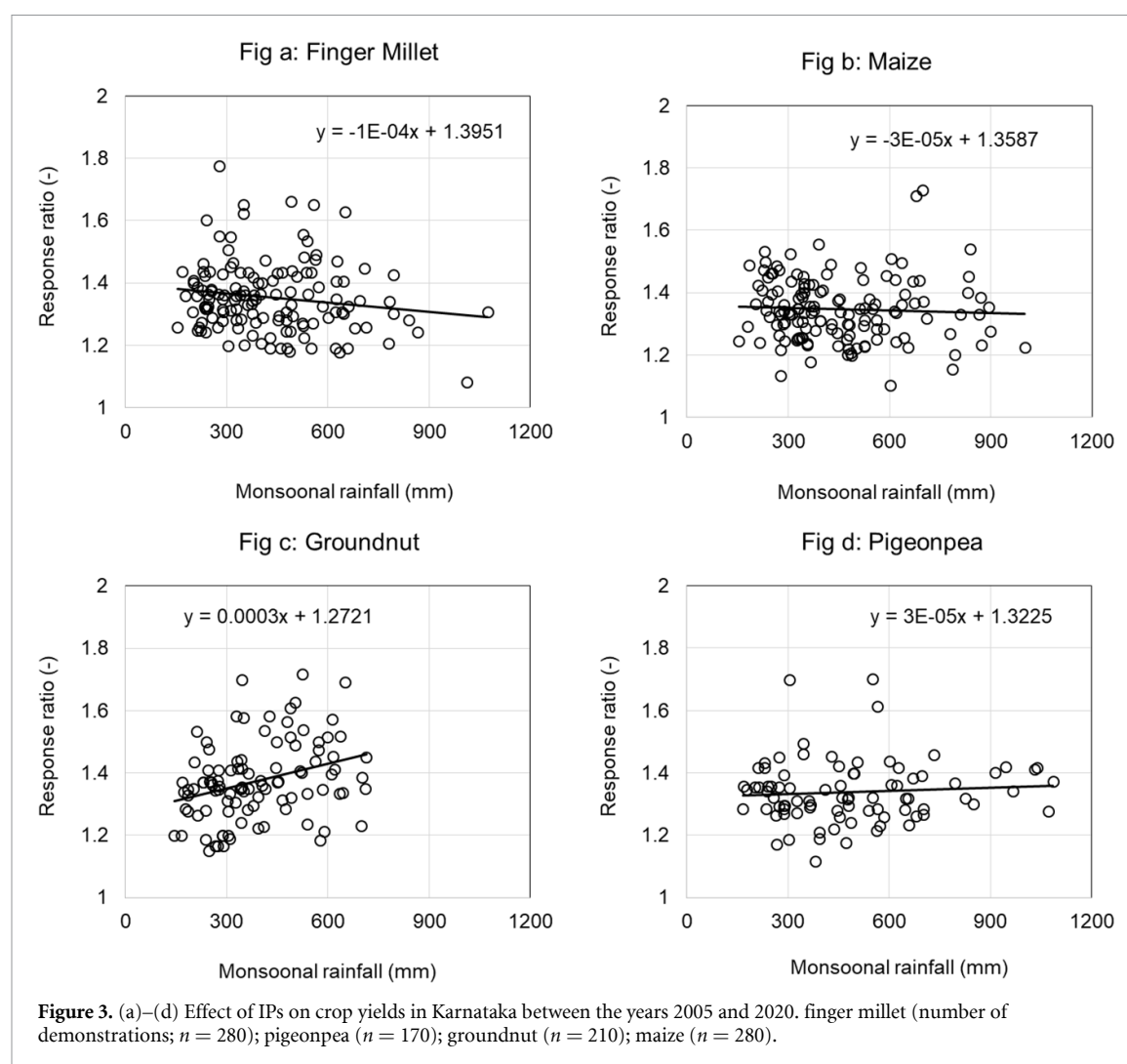
$$\begin{aligned} \text{Net income (US\$ ha}^{-1}\text{)} \\ &= \text{Crop yield (Kg ha}^{-1}\text{)} \\ &\quad \times \text{Market price (US\$ kg}^{-1}\text{)} \\ &\quad - \text{Cost of cultivation (US\$ ha}^{-1}\text{)}. \quad (2) \end{aligned}$$

The cost of cultivation data includes tillage operation, seed and fertilizer cost, energy cost, labour involved in sowing, irrigation application, interculture operations, harvesting was collected through farmers' interviews. Minimum support price of different crops for respective years was taken from the

Directorate of Economics and Statistics, Ministry of Agriculture and Farmers Welfare, Government of India for market price (Government of India 2020).

3. Results

The analysis of the 110 000 soil samples revealed widespread deficiencies not only in secondary nutrients, but also in micronutrients and soil OC. Figure 2 shows the spatial variability of different soil nutrients in different sub-districts of the state. Soils were mostly deficient in available zinc, boron, and sulfur. Phosphorous deficiency was found largely in the northwestern districts. OC in the soils ranged from 0.25% to 1.50%. The Western Ghats are relatively good in soil OC, which could be due to the vast forest cover, humid environment, and plantation crops. The diagnoses revealed rampant secondary and micronutrient deficiencies—52% in sulfur, 55% in zinc, and 62% in boron. Deficiencies in available sulfur, boron, and zinc were more widespread than those of macronutrients such as available phosphorous and potassium.



The impact of improved technologies (soil health management, resource use efficiency, and improved crop cultivars) that were promoted for select cereals (finger millet and maize), oilseeds (groundnut) and pulses (pigeonpea) is shown by presenting response ratio in figures 3(a)–(d). Improved technologies increased crop yields by 10%–60%. The response ratio demonstrated yield gains in all the crops due to treatment effects which varied with amount of rainfall. Groundnut pod yield increased with increasing rainfall (up to 800 mm) as evident from the response ratio. On the other hand, finger millet's response to micronutrient application was found to have a maximum at up to 600 mm rainfall. While finger millet, which is susceptible to waterlogging, saw a reduced response ratio with increasing rainfall, in pigeonpea and maize the response ratio was consistent with increasing rainfall. The statistical analysis demonstrated the significant difference in crop yield between IP and FP (table 1).

Data collected on land and water management interventions clearly indicate that the broad-bed and furrow (BBF) system could help enhance yields in different dryland crops. Figure 4 shows

the mean increase in crop yields in groundnut (100–150 kg ha⁻¹), soybean (250 kg ha⁻¹), sorghum (700 kg ha⁻¹), and pigeonpea (200 kg ha⁻¹) by sowing on BBF or raised beds. BBF helped enhance soil moisture besides protecting the crop from waterlogging in the event of heavy rains, which are common in the semi-arid tropics. Statistical results indicated that there is a significant difference in mean and variance in yield of all the selected crops except sorghum (table 1).

An improved method of DSR was promoted using the zero-till multi-crop planter along with weed management. Data collected from one of the districts (Dharwad) showed that crop yield was comparable to the conventional method, while a reduction was noted in the cost of cultivation by US\$ 150 ha⁻¹, saved irrigation amount by 300–400 mm, and equivalent energy requirement (~500 kWh ha⁻¹) compared to TPR. The economic gain from DSR increased by US\$ 100 ha⁻¹ compared to TPR (figure 5). Our analysis further showed that actual evapotranspiration in DSR was 500–700 mm compared to 1000–1200 mm in TPR. Due to its better establishment of root growth, DSR has been found resilient to extreme

Table 1. ANOVA (*F* value) showing effects of different NRM technologies on crop yield (significant at $p < 0.05$).

Technology	Crop	Groups	N	Mean	Variance	<i>P</i> -value	<i>F</i>	<i>F</i> crit
Soil health management (figure 3)	Finger millet	Treated	138	1440	480 214	0.0001	25.5	3.8
		Control	138	1937	851 017			
	Maize	Treated	136	4289	3 718 970	0.0001	27.4	3.8
		Control	136	5708	6 263 901			
	Groundnut	Treated	104	1077	576 872	0.0012	10.6	3.88
		Control	104	1490	1 082 502			
Resource use efficiency	Pigeonpea	Treated	85	902	259 223	0.001	10.9	3.9
		Control	85	1202	438 940			
	Groundnut	BBF	30	1098	69 505	0.05	3.89	4.0
		Flat	30	1235	75 112			
	Soybean	BBF	10	813	9104	0.0001	50	4.4
		Flat	10	1201	20 869			
Resource use efficiency	Sorghum	BBF	10	1713	736 076	0.12 ^a	2.5	4.3
		Flat	11	2348	901 100			
	Pigeonpea	BBF	50	989	48 773	0.001	10.7	3.9
		Flat	50	1149	70 023			
	Rice	DSR	110	2789	54 947	0.013	6.3	3.9
		TPR	110	2608	60 833			
Improved crop cultivars	Groundnut	Control	144	1425	397 083	0.0001	76.9	2.61
		Only cultivars ^b	585	1353	522 454			
		Only management	60	2262	448 126			
		Cultivars+ mgt	403	2038	851 866			
	Finger millet	Control	441	1898	578 295	0.000	181	2.61
		Only cultivars	456	2067	581 187			
		Only management	150	2492	490 368			
		Cultivars+ mgt	480	3097	1 070 025			
	Maize	Control	23	3645	1 089 756	0.008	5.08	3.1
		Only cultivars ^b	26	3599	1 401 048			
		Cultivars+ mgt	27	4459	1 112 668			
	Sunflower	Control	69	668	57 581	0.000	225.2	2.64
		Only cultivars	67	1079	59 765			
		Only management	19	1723	49 785			
		Cultivars+ mgt	50	1696	49 033			

^a Not significant^b Post-hoc test indicated no significant difference in groundnut ($p = 0.78 > p_{\text{threshold}} = 0.125$) and maize ($p = 0.89 > p_{\text{threshold}} = 0.016$) among control vs. cultivars at 0.05 significance level.

events such as flash floods when compared to TPR (Sharma 1995). The statistical results also indicated a significant difference in the cost of cultivation and net income between DSR and TPR.

Figure 6 shows the impact of IPs in groundnut, finger millet, maize and sunflower. The application of balanced nutrients based on soil tests boosted stagnant productivity levels. Farmers realized additional crop yields of 200–500 kg ha⁻¹ (10%–15% of total production) with minimal investment (less than US\$ 10 ha⁻¹) within a season, and were receptive to the technology. Improved crop cultivars along with land and water management further enhanced the yield levels. However, they required higher technical skills to adopt and hinged on the timely availability of improved crop cultivars.

Data revealed that more than the cultivars, IPs helped enhance crop yields. In groundnut, yield increased from 1500 to 2000 kg ha⁻¹ due to IPs. Similarly, maize farmers could harvest an additional 700–800 kg ha⁻¹ due to these practices. The introduction of new millet cultivars and better management practices increased millet yield by 1000 kg ha⁻¹.

Similar results were observed in sunflower. These results were confirmed with statistical tests that showed a significant difference in mean between treated and control fields (table 1). Further, post-hoc test revealed that except cultivars (control vs. cultivars) in groundnut ($p = 0.278$) and maize ($p = 0.89$), other technological treatment pairs (control vs. only management; control vs. cultivars and management) are significantly different at 0.05 threshold. For finger millet and sunflower all technological treatments were found significant as revealed by post-hoc test.

4. Discussion

Our experiences in striving to transform agriculture in Karnataka have confirmed that merely using better crop cultivars cannot lead to much gain. However, when better crop cultivars are promoted together with best management practices such as balanced fertilizer application and moisture management, the cycle of poor yields can be broken. Data gathered from a large area over 15 years has clearly showed that a holistic and integrated approach is essential for

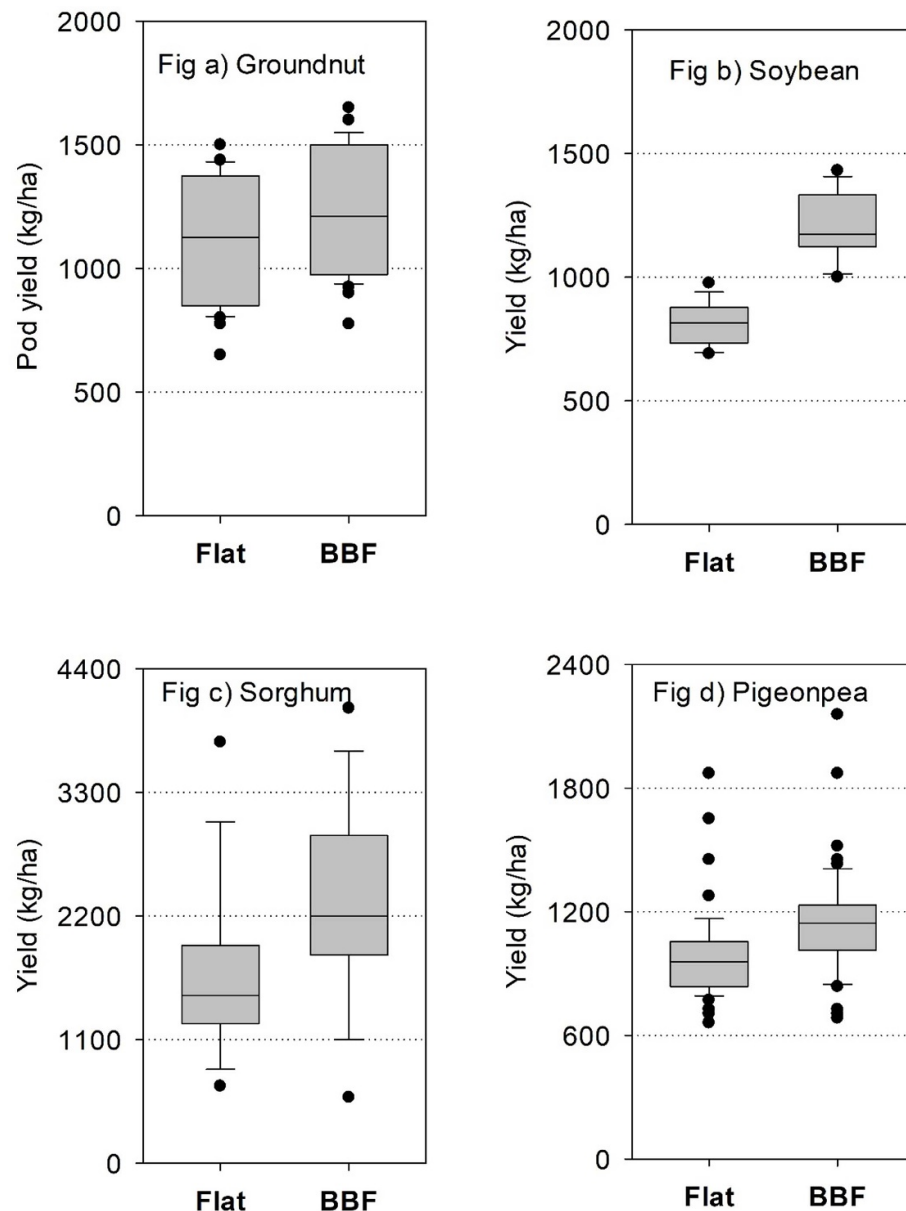
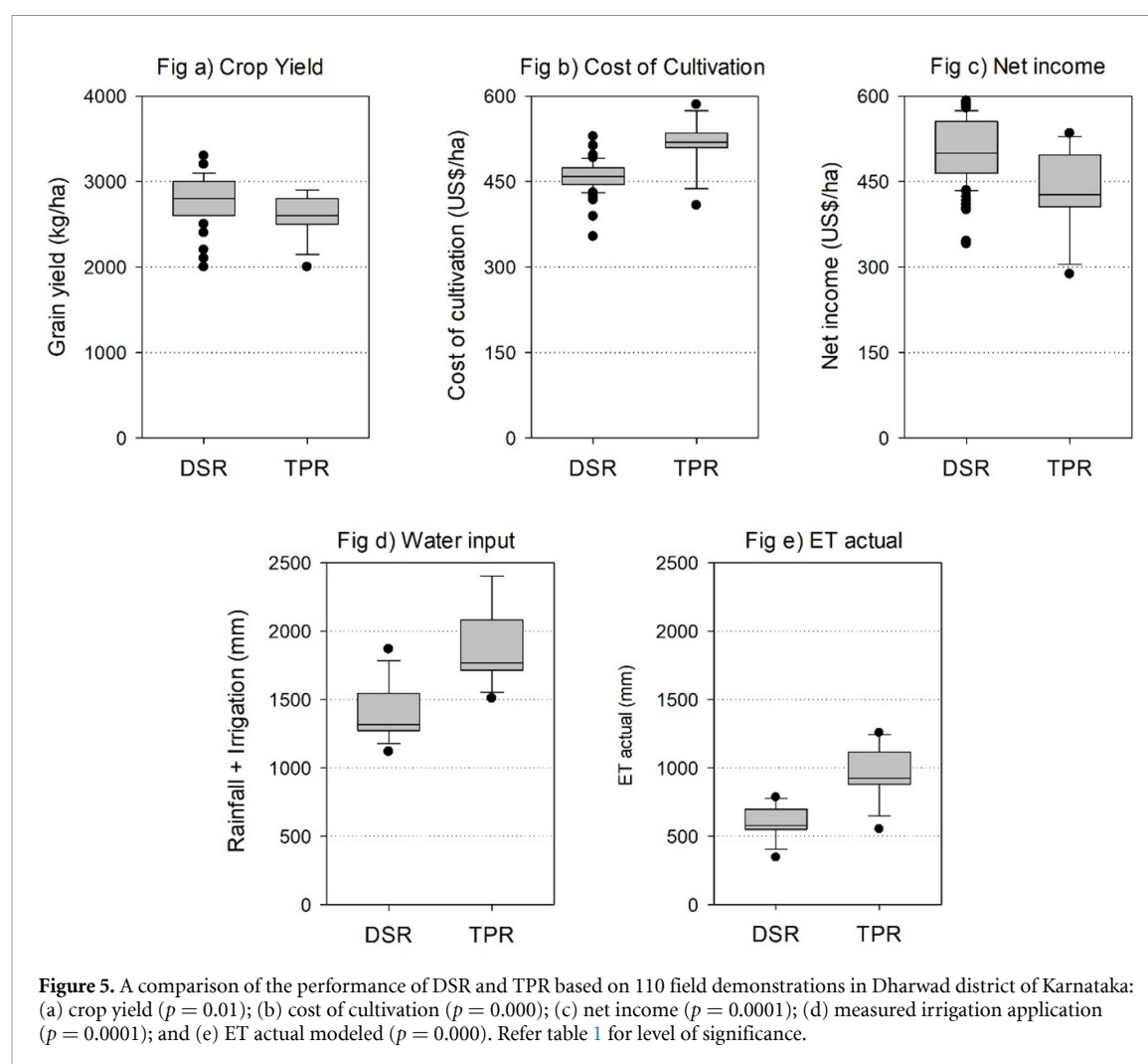


Figure 4. The impact of BBF method on yields of groundnut ($n = 60$), sorghum ($n = 21$), soybean ($n = 20$), and pigeonpea ($n = 100$) in Karnataka.

achieving growth in agriculture, with yield gains that can range from 20% to 80%. Although some of the resource conservation practices did not show significant yield gains, they contributed substantially to reducing the cost of cultivation and the pressure on available natural resources. For example, DSR practices reduced cost of cultivation significantly by minimizing labor involvement, water and energy inputs equivalent to US\$ 100 to 150 ha⁻¹. This helped farmers achieve 20%–30% additional benefits while reducing the pressure on water and energy requirements. Sustaining such gains achieved due to the adoption of IPs is possible. This will involve promoting cost and resource saving technologies that will help make agriculture profitable. Similarly, efforts made on soil testing and developing a soil map atlas of different nutrients across the state helped stakeholders to

realize the importance of balanced fertilizer use, otherwise they were largely following common recommendations across districts. Farmers, especially in irrigated systems, use fertilizers indiscriminately in order to achieve higher productivity. This practice results in land degradation, the pollution of surface and groundwater, and poor nutrient use efficiency, as 60%–70% of the fertilizer applied is lost through various channels (Khan *et al* 2018). Furthermore, poor soil nutrient status combined with a poor understanding of nutrient uptake patterns in different cropping systems forces farmers in drylands to use fertilizers without any rationale, resulting in poor nutrient use efficiency and increased cost of cultivation (Dimkpa *et al* 2020).

Farmers who had invested heavily only in major nutrients (nitrogen, phosphorous and potassium)

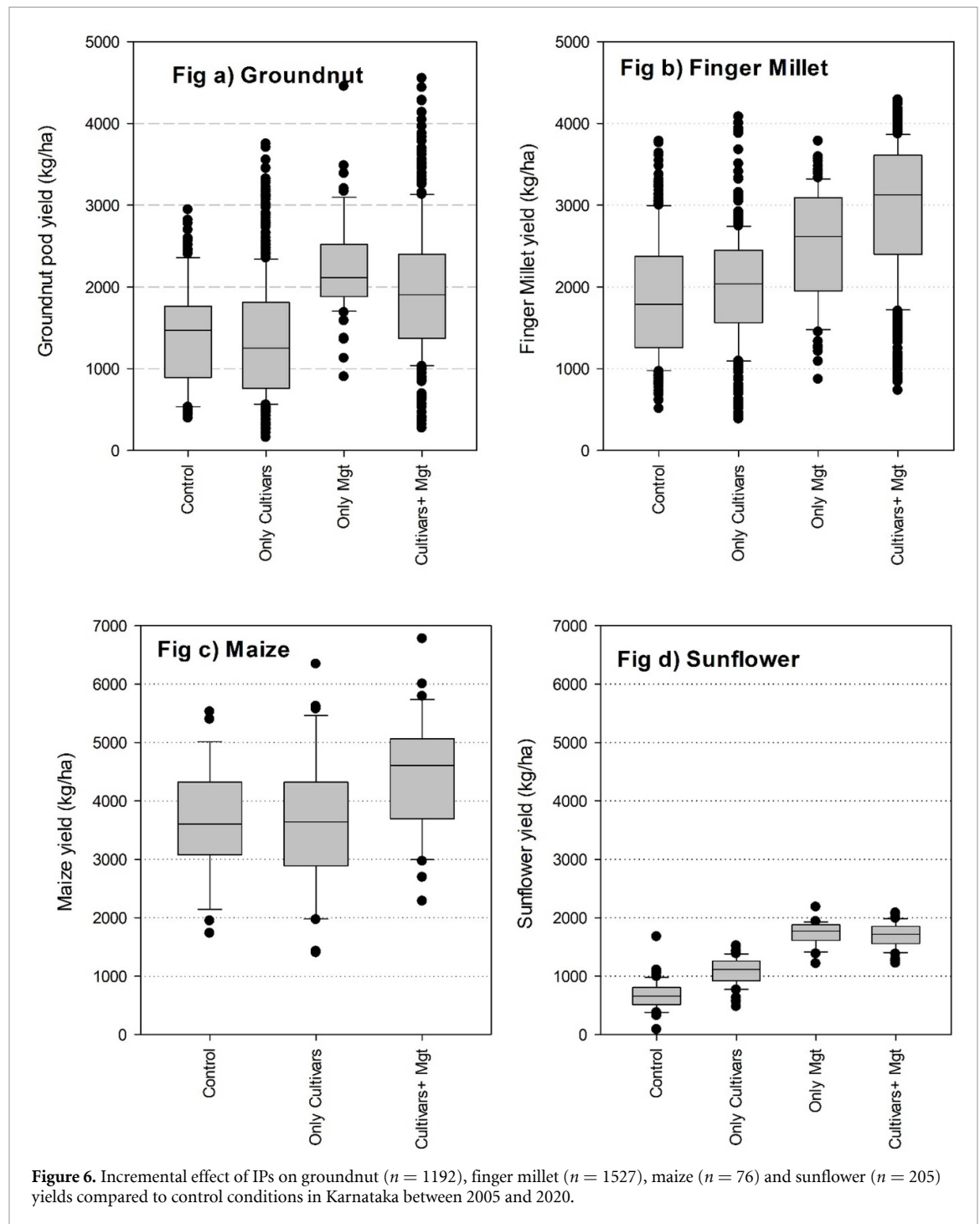


were convinced to also use micronutrients. Well-planned, site-specific nutrient management demonstrations reducing farmer investment on fertilizers and increased productivity, as was demonstrated over a crop production cycle. Kumar *et al* (2018) have clear evidence of micronutrient application leading to improvement in the quality of produce. Micronutrient application is also known to build resilience towards climate aberrations and disease infestation (Rehman *et al* 2016, Ullah *et al* 2018, Nadeem and Farooq 2019). Large scale soil sampling helped to recommend crop specific cluster level (group of villages) recommendations those are belonging to similar rainfall, soil types, cropping systems and farming practices. Such innovations not only enhanced the crop productivity but also reduced indiscriminate use of fertilizer consumption and reduce the cost of cultivation (Wani *et al* 2017).

Rainfall in Karnataka is highly erratic both in terms of its amount and distribution. Drylands in the state generally experience 2–3 dry spells ranging from 5–15 d in a season, which may lead to water stress in crops (Singh *et al* 2014, Mallya *et al* 2016). *In-situ* water management interventions such as BBF enabled the harvesting of

additional surface runoff and enhanced soil moisture availability. Data from hydrological monitoring at selected sites show that a minimum of 50 mm additional water was harvested due to such interventions, alleviating the effect of dry spells for an additional 5–8 d.

The results obtained in the current study are in close agreement with those of previous studies undertaken for reducing the yield gap in similar agro-ecological regions in India and elsewhere (FAO and DWFI 2015, Fischer 2015, Fischer and Connor 2018). Previous approaches based on single inputs, practices or genotypes can only be partial solutions, and Anderson *et al* (2016) recommended sustainable yield improvement by employing a range of methods appropriate to specific agro-ecological conditions. They also recommend farmer participatory technology demonstration for a wider dissemination strategy. Similar to our findings, other studies undertaken across the Indian subcontinent have indicated that DSR saves irrigation water ranging from 70–515 mm depending on soil types and crop management practices (Jat *et al* 2009, Gathala *et al* 2011, Kumar and Ladha 2011) and raised beds can enhance additional moisture availability ranging from 10 to



160 mm (Jat *et al* 2011, 2013, 2019, Singh *et al* 2018; Sepat *et al* 2017).

Increase of crop yields does not always involve high investments. Optimum use of resources together with adoption of appropriate technologies are key to enhancing system productivity (Gars and Ward 2019). For example, in the case of rice fallow management, available moisture was lost due to evaporation before the technology intervention. Introduction of short duration pulses using a zero till multi crop planter facilitated the utilization of about 150–250 mm of residual soil moisture. This was a significant contribution in terms of enhancing land and

water use efficiency while also contributing to crop intensification (Rockström 2003, Kar and Kumar 2009, Garnett *et al* 2013, Jägermeyr *et al* 2016, Chen *et al* 2018, Jat *et al* 2019, Stomph *et al* 2020). The scaling up clearly showed the impact of various best management practices on crop yield in different agro-ecological regions. Some of the technologies were relatively easy to demonstrate whereas others required trained human resources and capital investment on machinery and capacity building. Multi-institutional partnerships have been instrumental in the adoption process. Knowledge generating institutions such as state agricultural universities, and

national and international research institutes have significantly contributed by associating with knowledge dissemination institutions such as the development departments of governments to share new knowledge. A large number of demonstrations within a cluster (group of villages) provided insights into the variability in outcomes for stakeholders to gain clarity on the performance of the technology. The lessons from the study will be useful for addressing similar ecologies of other Asian and African countries that are seeking to bridge the yield gap and aiming to achieve United Nations SDGs by 2030.

5. Conclusion

This paper describes the impact of various farm scale NRM interventions on crop yield, income and resource use efficiency in diverse agro-ecological regions of Karnataka in India. Large-scale soil nutrient mapping showed widespread deficiencies in secondary and micronutrients, which was one of the important reasons for the stagnant yields. More than 50 000 farmers' participatory demonstrations on NRM interventions were undertaken between 2005 and 2020. Various *in-situ* rainwater harvesting interventions (BBF) and water saving technologies (DSR) were found effective in mitigating mid-season droughts and helped crop intensification. Crop yields showed consistent increases though these varied by 20%–80% with the combination of these technologies. In addition, the cost of cultivation was reduced by the application of fertilizers based on soil tests and the adoption of best management practices. This framework can be adopted to scale up best management practices and bridge yield gaps in dryland areas elsewhere in India and in drylands globally. The findings of this study will help sensitize policymakers and stakeholders on the benefits of adopting a science-based approach to NRM and address food security, land degradation and poverty issues in dryland regions.

Data availability statement

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

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