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Landscape resource management for sustainable crop intensification

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Abstract

Crop intensification is required to meet the food demands of an increasing population. This paper presents data from three paired scaling-up initiatives to compare the benefits of landscape-based interventions over individual plot-level interventions using evidence generated in the Indian semi-arid tropics. A range of soil and water conservation interventions were implemented in a decentralized manner following the landscape-based approach. The plot-level approach focused only on balanced fertilizer application and improved crop cultivars while the landscape-based interventions primarily addressed moisture availability, which was the key to reducing risks of crop failure besides aiding productivity gain and enhanced land and water-use efficiency. These interventions have additionally harvested 50–150 mm of surface runoff and facilitated groundwater recharge in 550–800 mm rainfall zones. Individual plot-level interventions also improved the crop yield significantly over the control plots. However, crop intensification was not achieved due to limited moisture availability. Landscape-based interventions produced 100%–300% higher crop production per year, greater income generation (>100%), and improved water productivity. Landscape-based interventions were also found to be beneficial in terms of reducing soil loss by 75%–90% and improving base flow availability additionally by 20–75 d in a year compared to untreated watersheds. With increased moisture availability, fallow lands in respective watersheds have been utilized for cultivation, thereby enhancing crop intensification. The findings of the study provide critical insights into the design of approaches suitable for scaling-up projects in order to both create impact and target the United Nations Sustainable Development Goals.

1. Introduction

Food, food security and the conservation of water resources are deeply embedded in the sustainable development goals that were set by the United Nations General Assembly in 2015. Global population is expected to touch 9.5 billion by 2050 and ensuring food security with a minimal water footprint is a major challenge that touches on many of these goals that are designed to achieve a sustainable future (Mekonnen and Hoekstra 2016, D'Ambrosio *et al* 2020, Gerten *et al* 2020, Hogeboom *et al* 2020). There is limited scope to expand agricultural land in many parts of the world as native grasslands, tropical rainforest, woodlands and wetlands have been converted to cultivation and planted pastures over past five decades (Rockstrom *et al* 2009, Niu *et al* 2019). Such changes have resulted in increased food grain production and ensured food self-sufficiency in different regions (Jägermeyr *et al* 2017). However, there are negative impacts of massive change in land use, including changes to hydrological cycles at global, national and regional scales, loss in biodiversity and alteration in bio-geochemical cycle of carbon nitrogen and phosphorus elements, and human induced climate change (Gleeson *et al* 2012, Famiglietti 2014, de Graaf *et al* 2019). Many of these control variables have either crossed or are fast approaching the planetary limits (Rockstrom *et al* 2009). The challenge, therefore, is how to bring a balance between increasing demand and dwindling resource availability without affecting ecosystem services (Ferrant *et al* 2014, MacDonald *et al* 2016).

A number of studies have indicated that there is a large yield gap in agriculture globally, especially in dryland areas. This includes India semi-arid farming areas, where grain production typically below 1500 kg ha yr^{-1}, which is lower than the achievable potential of 3000–5000 kg ha yr^{-1} with available resources (Rockstrom and Falkenmark 2015, Anantha *et al* 2021a). It has been argued that improvements could be achieved through enhanced resource use efficiency, particularly by the introduction of improved management practices (Gerten *et al* 2020, Anantha *et al* 2021b). Such improvements in efficiency are possible as part of a second Green Revolution that incorporates adoption of an integrated genetic and natural resource management approach (Rockström 2003, Senapati and Semenov 2020). The first Green Revolution in the 1960s largely focused on irrigated ecologies, but the second Green Revolution needs to focus on both irrigated and dryland systems with enhanced resource use efficiency (Davis *et al* 2017, Shekhar *et al* 2020). Drylands in India are facing a number of challenges including water scarcity, land degradation, malnutrition, and poverty. With climate change looming large, these challenges are further exacerbated (Fritz *et al* 2019). Natural resource management interventions are one of the adaptation strategies for dealing with climate change challenges (Halofsky and Peterson 2010, Poff *et al* 2016, Strassburg *et al* 2020, Anantha *et al* 2021c).

A number of scaling-up programs designed to achieve United Nations sustainable development goals are being implemented across Asia and Africa, aiming to address issues of food security, land degradation, malnutrition and poverty through a combination of public and private investment (Jägermeyr *et al* 2017). Most of these programs are focusing on selected components such as soil fertility improvement, crop varietal replacement/promotion and other agronomic practices, which mostly operate on individual farmers' plots (Abera *et al* 2020, Kumar *et al* 2020). In this paper, these are referred to as plot-level interventions. In addition, several programs are being implemented at a landscape scale, which largely consider hydrological units as one entity, in which soil protections, crops, livestock and trees are integral parts of the interventions (Garg *et al* 2020). These are referred as landscape-based interventions. The landscape-based approach offers opportunities for resource augmentation by conserving available resources, and it also helps to enhance the productivity at the plot-level by promoting improved management practices. However, thus far various services generated exclusively by a landscape-based approach and a plot-level based approach have not been quantified and compared (Glendenning and Vervoort 2010, Fritz *et al* 2019, Mastrángelo *et al* 2019). The quantification and comparison presented here will help to prioritize the strategies towards achieving sustainable crop intensification.

There is increasing interest among researchers across Asia, Africa, Latin America, Europe and other parts of the world to explore opportunities to address food security, environmental challenges and social wellbeing through landscape resource management approaches (Sayer *et al* 2013, Estrada-Carmona *et al* 2014, Milder *et al* 2014, Freeman *et al* 2015, García-Martín *et al* 2016, Zanzanaini *et al* 2016, Carmenta *et al* 2020, Reed *et al* 2020, Wable *et al* 2021). A comprehensive review undertaken by Reed *et al* (2016) and Reed *et al* (2020) suggested that a landscape approach has considerable potential to meet social and environmental objectives at local scales while aiding national commitments to addressing ongoing global challenges. However, the evidence base within the scientific literature has remained limited despite considerable acceptance for landscape approaches (Reed *et al* 2020).

This paper synthesizes results obtained from three paired scaling-up initiatives carried out in semi-arid region of India that have been implemented since 1999 by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and its consortium partners (figure 1). The plot-level approach was targeted to bridge the yield gap through the demonstration of a range of improved management practices (balanced fertilizer application and improved cultivars along with agronomic management practices) at an individual plot-level, along with capacity building. In parallel, a landscape-based approach followed another set of initiatives in which, along with productivity enhancement interventions, decentralized rainwater harvesting interventions were targeted (Garg *et al* 2012, 2020, 2021, Singh *et al* 2014, Karlberg *et al* 2015). For both approaches, biophysical, agronomic, hydrological, meteorological, socio-economic parameters were intensively monitored (Garg *et al* 2020, 2021). The overarching goal of this paper is to ascertain and compare differences between the landscape-based approach and the plot-level approach in terms of (a) resource creation, (b) cropping intensity and (c) net income.

2. Materials and methods

2.1. Description of study sites

The three paired project sites are located in the different parts of the Indian semi-arid tropics. These sites face challenges of water scarcity, land degradation, poor agricultural productivity and low resource

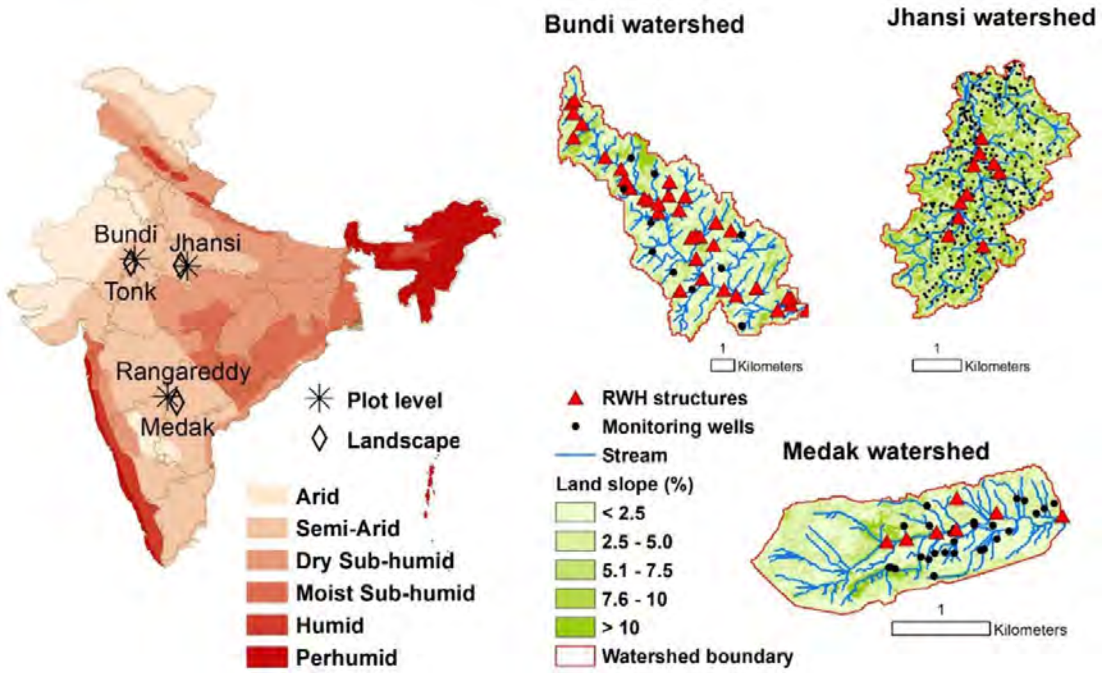

Figure 1. Location of study sites in the semi-arid tropical region of India following plot-level vs landscape-based approach; close-up maps shows land slope, stream network, location of rainwater harvesting structures and distribution of monitoring wells in treated watersheds under the landscape-based initiatives of the respective study districts; (Data source: climate classification in India by Raju *et al* 2013).

use efficiency (Garg *et al* 2012, 2020, Anantha and Wani 2016, Pathak *et al* 2016, Singh *et al* 2021). Out of three pairs, Bundi and Tonk districts are located in Rajasthan state representing western India; Jhansi in Uttar Pradesh in central India; Medak and Rangareddy in Telangana state in southern India. Location specific rainfall, soil types and demographic details are provided in table 1. Bundi and Tonk received annual average rainfall of 600 mm (ranging 370–690 mm) and 525 mm (ranging 380–610 mm), respectively. Medek and Rangareddy received annual average rainfall of 750 mm (between 465 and 1160 mm); and Jhansi received average rainfall of 800 mm (between 400 and 1270 mm) during the study period. Out of total annual rainfall, 80%–85% is received during monsoon season (June and September). Among these sites, villages located in west and central India had sandy/loamy soils with low water retention capacity and villages in southern India are having high clay content with high water retention capacity. The land uses of these sites are also different as villages from southern and central India are agriculturally dominated (>90% agriculture land) whereas villages in Western India have high fallow/waste land and only 35% area was under agriculture (table 1).

Groundwater is the only source of freshwater for agriculture and domestic use in these villages. Shallow dug wells (5–12 m deep and a diameter of 2–5 m) fed by perched water table serve about 4–10 ha area for supplemental irrigation. As these regions are characterized by hard rock geology with poor aquifer storage capacity (1%–3%), these wells were drying soon after the monsoon season and farmers were facing water scarcity especially during dry years and also in summer season and were suffering with poor agriculture productivity and low intensification (Marechal *et al* 2006).

2.2. Description of landscape-based vs. plot-level initiatives

To address the above challenges, ICRISAT and partners undertook technology demonstrations in a cluster of villages between 1999 and 2016 by following two-pronged strategies *viz*., (a) landscape-based interventions; (b) plot-level interventions. In landscape-based initiatives, the targeted interventions were implemented for 5 years whereas for plot-level initiatives, the interventions were undertaken between 3 and 5 years (table 1).

2.2.1. Landscape-based approach

2.2.1.1. Interventions implemented

Decentralized rainwater harvesting interventions were implemented by treating the land with appropriate landform treatments from ridge to valley. The landscape which has more than 2% slope was divided into smaller parts with earthen field bunds. About 1 ha area was divided into 3–4 parcels by forming earthen bunds to control runoff velocity and arrest soil loss. In addition, a range of gully control structures, farm ponds on the upstream fields were also

Table 1. Location, rainfall, soil types and demographic details in landscape-based and plot-level initiatives in different states, India.

State	Rajasthan		Telangana		Uttar Pradesh	
District	Bundi	Tonk	Rangareddy	Medak	Jhansi	Jhansi
Treatment type	Landscape-based	Plot-level	Landscape-based	Plot-level	Landscape-based	Plot-level
Latitude	25.5631	25.7729	17.3666	17.7083	25.4155	25.4
Longitude	75.4104	75.6307	78.1166	77.5714	78.3458	78.3
No. of villages	2	3	1	5	3	1
Annual average rainfall (mm) along with its range measured during project period	600 (370–690)	525 (380–610)	750 (460–1160)	750 (500–1070	800 (400–1270)	800 (400–1270)
Project duration	1999–2004	2010–2012	1999–2004	2013–2015	2012–2016	2012–2016
Total geographical area (ha)	5000	2500	465	500	1250	1100
Agriculture land (%)	35	32	90	75	95	70
RWH storage capacity (m^3)	1536 000	—	40 000	—	100 000	—
Aquifer storage, S (%)[a]	1–1.5	—	1–3	—	1–2	—
Soil characteristics						
Sand (%)	56	61	17.4	19	61	60
Silt (%)	30	25	19.8	20	20	21
Clay (%)	14	14	62.8	61	19	19
OC (%)	0.4	0.35	1.04	0.96	0.4	0.39
Soil depth (m)	0.6	0.9	0.4	0.5	0.75	0.70
No. of crop demonstrations	—	3000	—	1500	—	2200
Landholding size (% distribution)						
Marginal and small (<2 ha)	64%	66%	60%	61%	59%	60%
Medium (2–4 ha)	31%	29%	27%	25%	28%	29%
Large (> 4 ha)	5%	4%	13%	14%	13%	11%

[a] Adopted from (Marechal *et al* 2004, 2006, EPTRI and NGRI 2005).

constructed to check soil erosion and conserve soil moisture (Garg *et al* 2020, Singh *et al* 2021). In addition, traditional rainwater harvesting structures made of masonry check dams that have a storage capacity ranging from 2000 m^3 to 50 000 m^3 were constructed and community ponds were desilted and/or rejuvenated (figure 1). The total water storage capacity created in respective villages is shown in table 1. The geographical extent of these initiatives ranged from 500 to 5000 ha. A detailed description of the study area and the specific interventions that were implemented in Rangareddy, Telangana are available in Garg *et al* (2012); and Garg and Wani (2013); those implemented in Jhansi, Uttar Pradesh can be found in Garg *et al* (2020) and Singh *et al* (2021); and those implemented in Bundi, Rajasthan can be found in Garg *et al* (2021).

2.2.1.2. Data monitoring and analysis

An intensive data monitoring mechanism was implemented, involving a paired watershed approach in which one watershed was treated with landscape-based interventions (with interventions, figure 1) and the neighboring untreated watershed (no-interventions) was monitored to compare impact.

Rainfall is the only source of water in the study watersheds, which is partitioned into various water balance components based on different biophysical factors (soil type, land use and landscape topography). A portion of the rainfall, which enters into the vadose zone through infiltration process, enhances soil moisture availability; out of this, the surplus amount contributes to the groundwater recharge. Available soil moisture of vadose zone is utilized by vegetation (trees/crops) through transpiration and some of it is evaporated, together this is termed as evapotranspiration. After saturating surface soil, an overland flow is generated (also called as surface runoff), which moves along the slope. Rainwater harvesting structures (e.g. check dams and storage structures) retain a fraction of surface runoff and the rest spilled over to downstream locations. The monsoonal water balance components of the study watershed is defined in equation (1):

$$\begin{aligned}\text{Rainfall (mm)} = {} & \text{Surface runoff (mm)} \\ & + \text{Groundwater recharge (mm)} \\ & + \text{Actual Evapotranspiration (mm)}.\end{aligned} \tag{1}$$

Rainfall was monitored by establishing meteorological stations and automatic runoff gauges were established at different micro watersheds of treated landscape ranging from 50 to 500 ha. For runoff gauging, a stilling well was constructed at the outlet of the watershed and a mechanical type stage recorder or an automatic pressure transducer, i.e. DIVER (pressure transducers for stage recording, Model DI801 TD) was placed at the bottom of the stilling well (Garg *et al* 2020, Singh *et al* 2021). The DIVER was programed to record pressure at the head at 15 min intervals. The measured pressure head was used to estimate spillway discharge (i.e. outflow from the watershed) by using equations (2) and (3)

$$\text{Spillway discharge, } Q_t\left(\frac{\text{m}^3}{\text{sec}}\right) = 1.705\, x\, L\, x\, (h_t)^{1.5}. \tag{2}$$

where L is length of the rectangular weir and h_t is depth of runoff layer passing from gauging station at a given time;

$$\begin{aligned}\text{Spillway volume } \left(\text{m}^3\right) = {} & \text{spillway discharge, } Q_t\left(\frac{\text{m}^3}{\text{sec}}\right) \\ & x \text{ time interval (sec)}.\end{aligned} \tag{3}$$

Further, the volume of water harvested in different structures was estimated from pressure head data collected through DIVER. The relationship between depth vs. storage capacity and depth vs surface area which was established by undertaking a topographic survey used to convert measured depth into storage volume.

The water table fluctuation (WTF) method is a well-accepted technique for estimating groundwater recharge in hard rock regions (Pavelic *et al* 2012, Garg and Wani 2013, Tilahun *et al* 2020). The water table of all the dug wells located in project villages (i.e. 20–388 wells/site)were measured using water level indicators on a monthly time scale and groundwater recharge was estimated using equation (4)

$$R = (\Delta h * S)/100 + W. \tag{4}$$

where R is the net groundwater recharge (mm), Δh is the change in hydraulic head before and after the monsoon period (m), S is the aquifer storage (%), W is the water withdrawal during the monsoon period (mm).

The value of aquifer storage (S) was taken from earlier studies undertaken by National Geophysical Research Institute and other researchers (Marechal *et al* 2004, 2006, EPTRI and NGRI 2005). Whereas DIVERs were placed in selected wells to measure pumping hours in different cropping system for quantifying water withdrawal (refer., Singh *et al* 2021) in monsoon and post monsoon seasons.

Hydrological data were analyzed to understand the rainfall-runoff relationship under dry, normal and wet years. These categories of rainfall were differentiated as follows: (a) less than 20% of long term average = dry or deficit years; (b) greater than 20% of long term average = wet or surplus years; and (c) in between ±20% of long term average = normal year in respective ecologies (IMD 2010). The impact of surface runoff due to upstream rainwater harvesting interventions were estimated by comparing outflow in treated (with interventions) and untreated (no-interventions) landscapes in respective watersheds. Similarly, change in hydraulic head, which reflects the groundwater availability in shallow dug wells was compared in both treated and untreated watersheds. Surface runoff and groundwater recharge were estimated for respective pilot sites in different years. In addition, efforts were also made to monitor soil loss by integrating sediment samplers with runoff monitoring. During the surplus rainfall event, sediment samples at the gauging stations were automatically collected at hourly intervals and stored in separate containers. These samples were analyzed in a laboratory for sediment concentration and estimated soil loss (Pathak *et al* 2016).

The change in land use and cropping intensity due to landscape-based interventions was captured through ground survey before and after the project implementation. A calibrated Soil and Water Assessment Tool (SWAT, a semi-process based hydrological model, Arnold *et al* 2012) was used for estimating actual evapotranspiration (ET) from respective project sites (Garg *et al* 2012, 2021, Garg and Wani 2013). To understand the irrigation scheduling for major cropping system, the of pumping hours were measured in selected fields using DIVER. This data was provided as input into a model to simulate the ET for different years.

Data were analysed to estimate water productivity in different years (dry, normal and wet years) for both landscape-based and plot-level approach in respective study sites by using equation (5)

$$\text{WP}_{\text{ET}}\left(\frac{\text{kg}}{\text{m}^3}\right) = \frac{\text{Grain yield }\left(\frac{\text{kg}}{\text{ha}}\right)}{\text{Actual ET (mm)}} \times \frac{1}{10}. \tag{5}$$

where grain yield (kg ha^{-1}) is measured for the field of 20 selected farmers during the *kharif* and *rabi* seasons in each of the watersheds. The detailed method of measuring crop yield using crop cutting is described in the next section.

2.2.2. Plot-level initiatives

2.2.2.1. Demonstrations details

In the plot-level initiatives, the focus was on optimizing available resources at individual plots for increased crop production through improved management practices. Soil test-based fertilizer application and use of improved crop cultivars were promoted. Soil samples (15–20 samples from 500 ha area) were collected by following stratified random sampling that considered the topography, landholding and cropping system from all the project sites and was analyzed for important plant available soil nutrients (available P and S, exchangeable K, B and Zn) and soil organic carbon (Walkley and Black 1934, Hanway and Heidal 1952). Based on the soil analysis results, farmer participatory technology demonstrations on balanced fertilizer application were undertaken. Additionally, improved crop cultivars were introduced for major crops (cereals, oilseeds, pulses). In this approach, a cluster of 3–5 villages were selected in respective districts and 200–250 farmer participatory technology demonstrations (>10 000 technology demonstrations in total) were laid out in each season to facilitate experiential learning for farmers to make them realize the productive potential of the cultivars and crop management practices. Technology demonstrations were undertaken over a minimum 3 year period in respective project sites in which about 50% of farmers were chosen as new participants every year to reach a maximum number of farmers, and the rest of the farmers were repeated at a minimum for two years. About 60% of the households in these villages are under small and marginal category with less than 2 ha of landholdings (table 1). Most of the demonstrations were associated with small and marginal farmers to enhance their capacity to adopt improved management practices.

2.2.2.2. Data monitoring

Under the plot-level approach, the farmers' fields were divided into two parts—a treated plot and a control plot to compare the impact of technology demonstrations. In the treated plot, balanced fertilizer application, improved crop cultivars or combination of both were demonstrated as per farmers' willingness and acceptability. Whereas in control plots, farmers followed their own practices. The technology demonstrations were undertaken under the close supervision of trained extension works and field scientists.

About 1000 crop cutting studies (50–80 per site per season) were undertaken to assess the impact of improved management practices on crop yield (Tek *et al* 2016). In this method, a 3 × 3 m area was demarcated along with three replications. Crop was harvested during the maturity to measure the grain and biomass yield. In addition, cost of cultivation (farm inputs, irrigation, labour, energy cost) data was collected through household survey of selected farmers and net income was calculated using equation (6)

$$\mathrm{NI_a} = \sum_{i=1}^{n} Y_i \times A_i \times M_i - A_i \times C_i. \qquad (6)$$

where, $\mathrm{NI_a}$ = net income (US$/HH/year); Y_i is crop yield (kg $\mathrm{ha^{-1}}$) for plot *i;* A_i is area of the plot *i* (ha); M_i is market price (US$/kg); C_i is cost of cultivation of plot *i* (US$/ha); n = number of plots farmers owning.

2.3. Statistical analysis

2.3.1. Landscape-based initiatives

Data of outflow, groundwater availability, soil loss and base flow measured on yearly time scale is compared among treated and untreated watershed using ANOVA. Further, a Chi-square test was performed to compare well-functioning status of dug wells among treated and untreated watersheds in respective project locations on monthly time scale. We divided all the dug wells into five categories based on water availability (i.e. hydraulic head, h): (a) dry; (b) $h < 1$ m; (c) $h = 1$–3 m; (d) $h = 3$–5 m; and (e) $h > 5$ m. The categorized data were used to check the level of significance between treated and untreated watersheds in respective sites.

2.3.2. Plot-level initiatives

Crop yield data of different crops obtained from treated and control plots were analyzed using ANOVA (Analysis of Variance) to understand the significance of crop yield due to the application of balanced fertilizer and crop cultivars over the control plots in respective project locations. Further, post-hoc analysis also performed to understand the impact among different treatment plots.

2.3.3. Comparing landscape-based vs plot-level impact

The total production and net income obtained from landscape-based and plot-level initiatives were compared over the untreated/control fields using ANOVA and post-hoc analysis.

2.4. Uncertainties of the results

Landscape hydrology is highly complex as is driven by various biophysical (topography and soil types) and land management factors. In the current study, emphasis was given on intensive hydrological monitoring; hence, surface runoff and groundwater recharge were measured using state-of-the art instrumentation. ET at landscape level was estimated in respective years as the balance closure of the water balance equation (refer equation (1)). However, ET at plot scale for different crops (e.g. maize, pearl millet, groundnut, etc) was estimated using simulation modeling, which may spatially vary due to inherent heterogeneity of the landscape and management

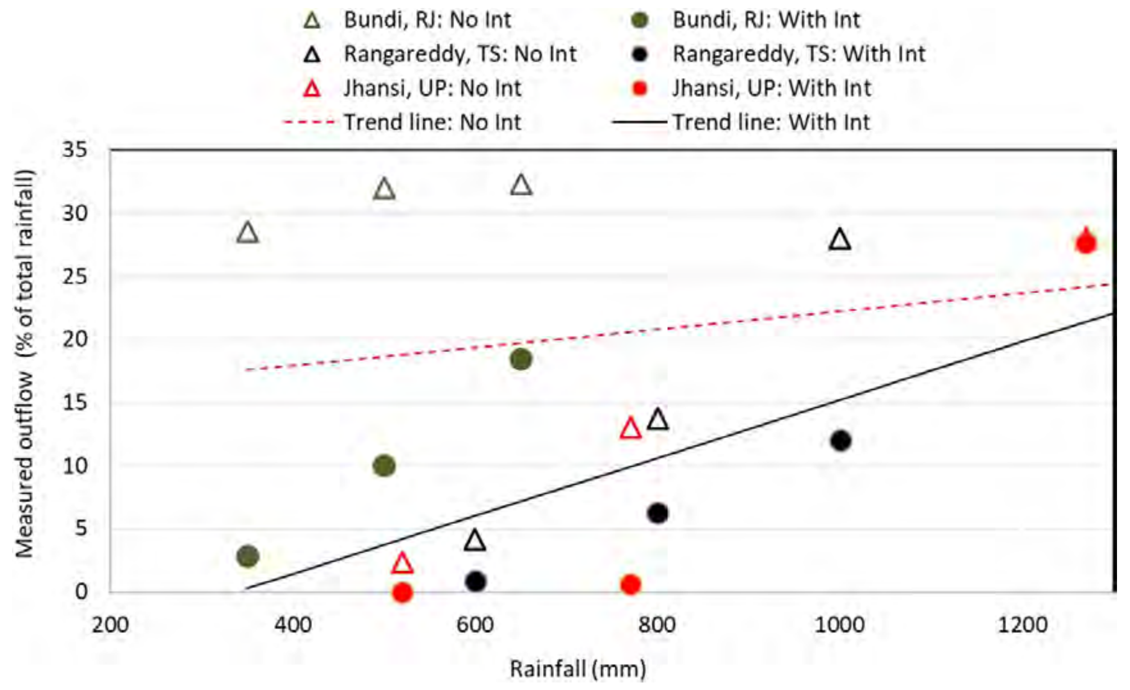

Figure 2. Measured outflow from treated and untreated landscapes in pilot villages; RJ: Rajasthan; TS: Telangana; UP: Uttar Pradesh.

practices. This may develop about 10%–15% uncertainty in ET estimation (i.e. ∼30–50 mm) as there could be variations in soil properties, management factors and supplemental irrigation from plot to plot in respective watersheds.

3. Results

3.1. Resource provision through landscape-based approach

The impact of interventions on generated outflow in the project villages are shown in figure 2. The circles and triangles indicates outflow measured with treated and untreated watersheds. The difference in the trend line indicates the change in outflow due to landscape-based interventions with different rainfall categories. Various landscape-based interventions have facilitated to harvest surface runoff within the landscape which is reflected in measured outflow. Landscape-based interventions harvested additional surface runoff ranging from 50 to 150 mm yr^{-1} depending on rainfall amount and intensity. The low rainfall watershed of Bundi district in Rajasthan (western India) in which rainfall ranging between 370 and 690 mm, outflow declined by 40%–90% due to landscape-based interventions in different years. The generated runoff in Bundi watershed was relatively higher compared to other districts due to its steep landscape and its land use dominated with waste or fallow land.

In Rangareddy (Telangana) and Jhansi (Uttar Pradesh) districts, which are 600–800 mm rainfall regions, the generated outflow largely decline during normal years. Runoff generated at 600 mm rainfall was negligible (<5% of total rainfall) as these villages are dominated by agricultural land use. Various landscape-based interventions in Rangareddy and Jhansi districts could harvest only marginal surface runoff in dry years. During normal years, the available runoff was 5%–15% of total rainfall in untreated watersheds, landscape-based interventions harvested about 40%–90% of generated runoff. Whereas the outflow generated with >1000 mm rainfall condition in wet years was in the range of 30% of total rainfall. Under this condition, the landscape-based interventions could partially harvest (10%–50%) generated runoff and rest was available for downstream uses.

Table 2 indicates that the landscape-based interventions have altered water balance components (outflow and groundwater availability) significantly ($p < 0.05$) between treated and untreated watersheds in the respective project sites. The harvested runoff due to landscape-based interventions primarily impacted on groundwater resource availability, both in terms of its amount and longevity. Figure 3 shows resource availability status in paired watersheds (with and without interventions) based on data collected from three study locations for dry, normal and wet years. Groundwater levels increased from 2.0 to 5.0 m and a minimum of 30% of the defunct wells were rejuvenated. In the watersheds without landscape-based interventions, the functioning percentage of shallow dug wells was less than 55% in most of the cases including in wet years. The runoff generated from the landscape quickly dissipates and therefore, in the untreated watershed, the groundwater recharge opportunities were limited

Table 2. ANOVA (F value) showing effects of landscape-based interventions on outflow, groundwater availability (hydraulic head in dug wells), soil loss and base flow (significant at $p < 0.05$).

SN	Parameter	Treated watershed	Untreated watershed	F value	F_{crit}	p-value	No. of events (N)
A	Rajasthan						
(i)	Outflow (% rainfall)	10	22	4.55	3.58	0.04	168
(ii)	Average hydraulic head in dug wells (m)	7.4	3.6	4.49	3.58	0.04	60
(iii)	Soil loss (t $ha^{-1}yr^{-1}$)	0.8	3.4	4.9	3.58	0.01	156
(iv)	Base flow after monsoon (no. of days)	35	12	19.1	4.49	0.00	—
B	Uttar Pradesh						
(i)	Outflow (% rainfall)	10	18	5.9	4.49	0.01	84
(ii)	Average hydraulic head in dug wells (m)	4.5	2.0	6.17	4.49	0.02	60
(iii)	Base flow after monsoon (no. of days)	110	35	28.7	4.49	0.00	—
C	Telangana						
(i)	Outflow (% rainfall)	6	14	8.5	4.49	0.02	134
(ii)	Average hydraulic head in dug wells (m)	5.0	2.4	6.29	4.49	0.02	66
(iii)	Soil loss (t ha^{-1} yr^{-1})	2.5	22	8.05	4.49	0.00	122
(iv)	Base flow after monsoon (no. of days)	85	25	32.8	4.49	0.00	—

(Sishodia *et al* 2017). Landscape-based interventions allowed sufficient time and space for the surface runoff to slow down and accumulate runoff water within the fields and this also regenerated the first order stream networks. Increased soil moisture and groundwater availability made it possible for farmers to cultivate crops during two seasons *viz*., monsoon (*kharif*) and post monsoon (*rabi*) instead of taking only one crop in a year. In addition, with increased groundwater availability, cultivable fallow lands were converted into productive lands. This development made it possible to increase the overall cropping intensity of the landscapes—from 80%–120% (untreated) to 140%–180% (treated), while significantly reducing the risk of crop failure. Soil loss after the implementation of landscape-based interventions was reduced by 75%–90% ($p < 0.05$; table 2) and enhanced the base flow additionally by 20–75 d ($p < 0.05$; table 2) in a year, which is important to sustain the perennial nature of riverine ecosystems.

Further, to describe the fluctuation in groundwater table on a spatial scale, we have presented data for one of the paired watersheds from Uttar Pradesh. Figure 4 summarized the water availability (hydraulic head) status of functioning wells over the year during 2014, 2015 and 2016 in treated and untreated watersheds along with the rainfall received. We categorized functioning wells into five groups based on available hydraulic head (water column in respective dug wells): (a) dry (b) poor (0–1 m); (c) moderate (1–3 m); (d) good (3–5 m) and (e) excellent (>5 m). In 2013 there was a total rainfall of 1276 mm, so it was classified as a wet year, whereas 2014, 2015 and 2016 received 520 mm, 404 mm and 768 mm respectively. As 2013 was a wet year (not shown in figure) both treated and untreated watersheds responded with 100% functioning well status. However, treated watersheds showed more than 85% of wells with hydraulic head status greater than 5 m compared to 32%–60% wells in untreated watershed under this category (up to October 2014).

In addition, about 10%–20% of dug wells were yielding excellent (>5 m head), 35%–40% good (3–5 m head); 20%–25% moderate (1–3 m); and less than 20% wells with less than 1 m hydraulic head in treated watersheds during June to September 2015. On the other hand, only 2%–5% of the total wells were in the excellent category (>5 m), less than 20% good (3–5 m head); 40% moderate; and 30%–50% wells were in poor yielding/non-functional category in untreated watershed during June to September 2015. The recharged water in shallow aquifers remained available for longer periods in treated watersheds compared to untreated watersheds. For example, despite receiving 520 mm and 404 mm rainfall in 2015 and 2016, a large percentage of shallow dug wells in treated watersheds were functioning. About 5%–18% wells were only dried in treated watersheds during October–December 2015 compared to 28%–38% in untreated watershed during the same period.

By February 2016, more than 40% of the wells were yielding, with moderate (1–3 m) to good (3–5 m) hydraulic head in treated watershed compared to only 17% in untreated watersheds. At any point of time, 20% of wells in treated watersheds were yielding

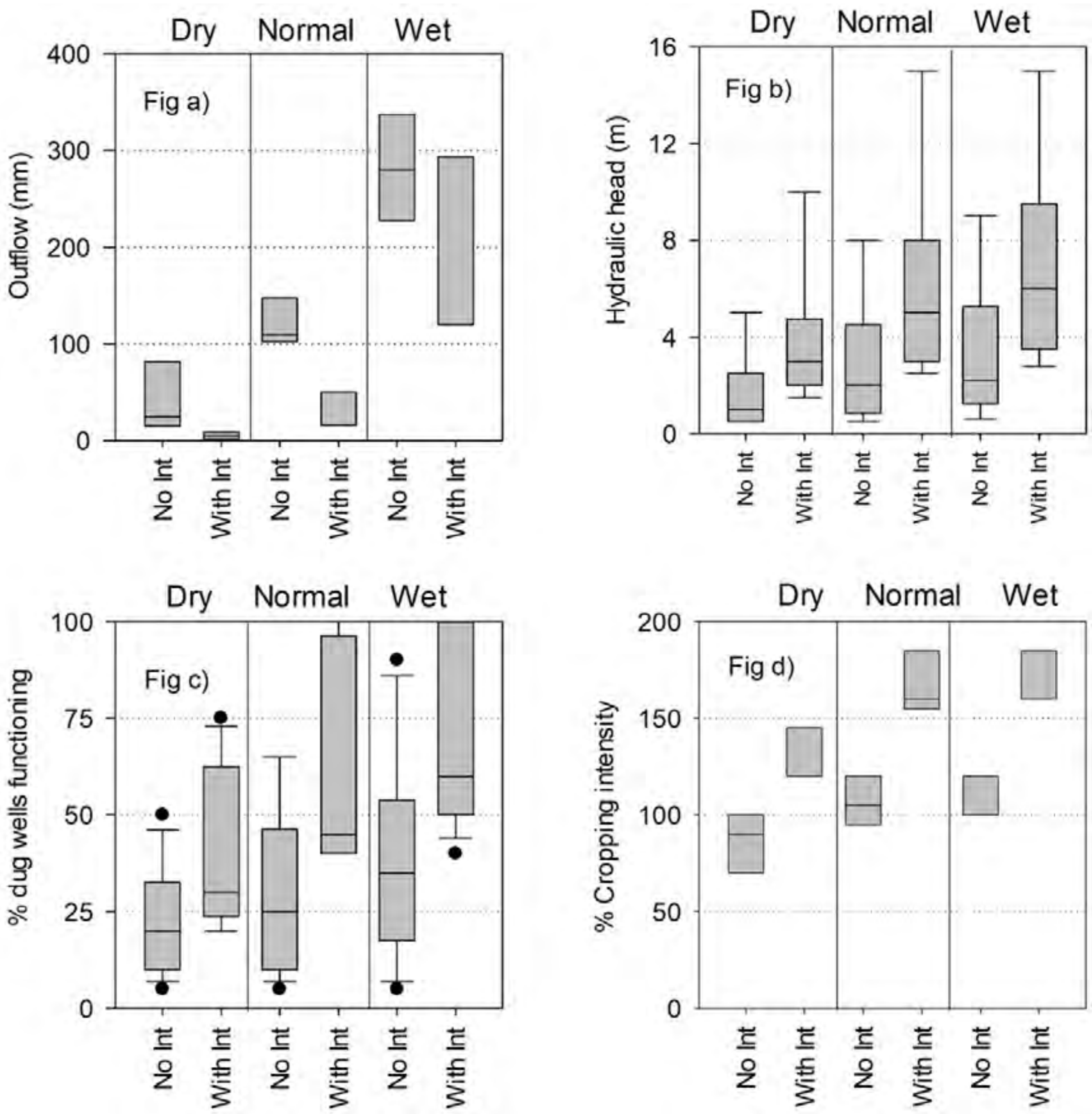

Figure 3. Resource availability status before and after landscape-based interventions—(a) generated outflow; (b) groundwater availability; (c) per cent functioning dug wells; and (d) cropping intensity.

a minimum amount with moderate status compared to 10% in untreated watersheds. During the beginning of the monsoon in July 2016, 35% of wells rejuvenated back to excellent, 40% to good and 33% to moderate in treated watersheds. Whereas, about 40% and 60% of wells were showing good and moderate yield status in untreated watersheds in July 2016.

The Chi-square statistics revealed that the functioning status of wells in treated watersheds of Jhansi (Uttar Pradesh) was significantly different from untreated watersheds (table 3). The difference in functioning wells was found highly significant among treated and untreated watersheds in all months except May 2016. As May 2016 was one of the driest months after two consecutive dry years i.e. 2014 and 2015.

Similar observations were also made in the other two project sites (Rajasthan and Telangana), with landscape-based interventions improving the functioning status of the dug wells with higher water availability (i.e. hydraulic head) (Garg *et al* 2012, 2021).

Figure 5 compares the area cultivated under different crops during dry, normal and wet years in *kharif* (monsoon) and *rabi* (post-monsoon) seasons in treated and untreated watersheds of Bundi (Rajasthan), Jhansi (Uttar Pradesh) and Rangareddy (Telangana) districts. With improved groundwater availability, the cropped area which was either single crop or left fallow has been brought into cultivation in both *kharif* and *rabi* season. Farmers in Bundi and Jhansi those largely prefer to cultivate *rabi* crops (mustard, chickpea, wheat, vegetables) were benefited to its full potential. The area under wheat (staple cereal crop in the region) doubled with assured water availability compared to nearby untreated watersheds. Whereas the area under mustard and

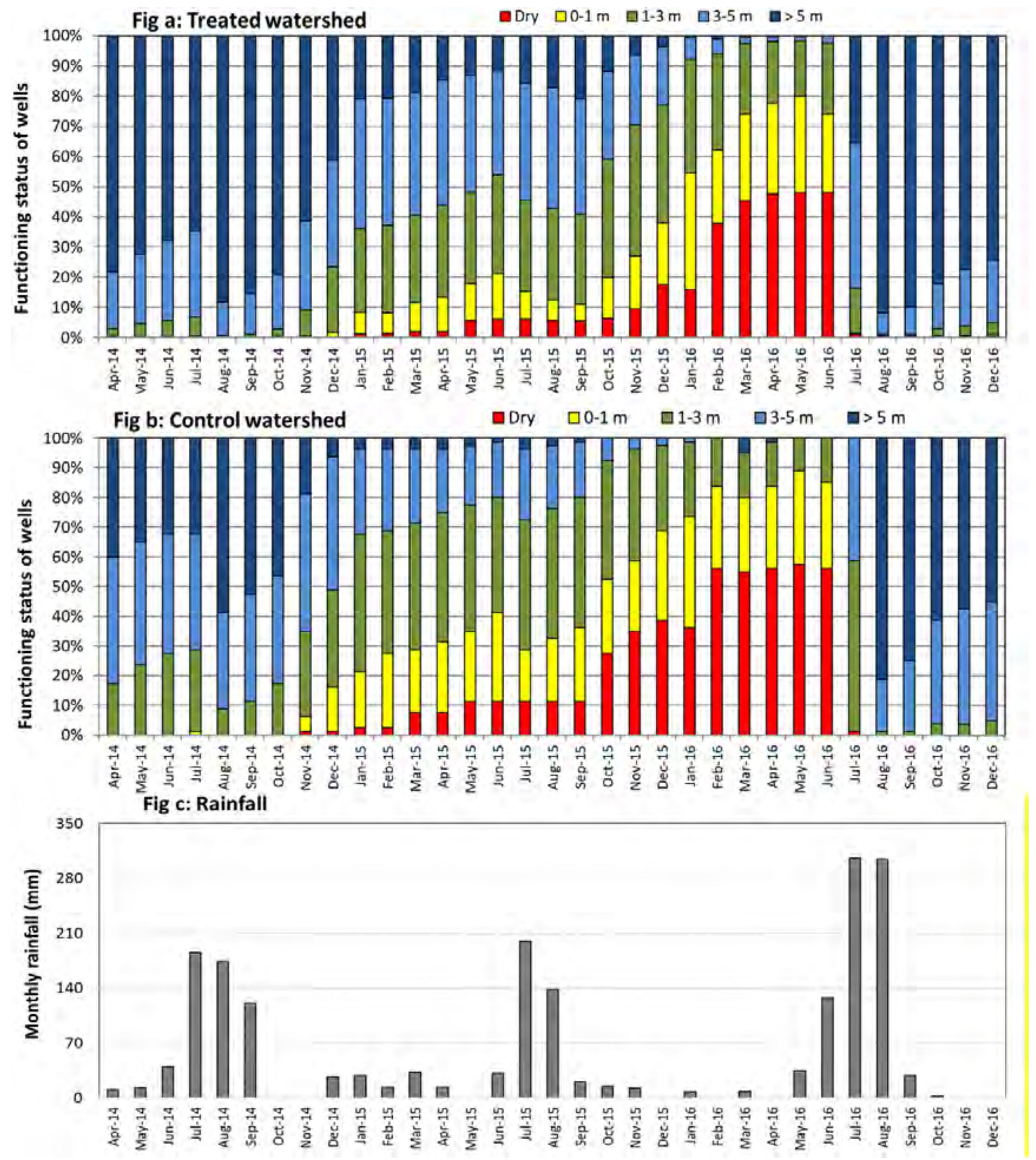

Figure 4. Percentage of total wells with functioning status in (a) treated and (b) untreated watersheds between 2014 and 2016 along with (c) monthly rainfall. Number of wells monitored in treated and untreated watersheds were 388 and 150 at Jhansi, Uttar Pradesh, respectively.

Table 3. Measure of the functioning status between the treated and untreated watershed using Chi square statistics (significance level 5%).

Year	Month	Test statistic	*p* value	*p* critical
2014	May	69	0.00	9.49
	Sept	45	0.00	9.49
2015	Feb	101	0.00	9.49
	May	75	0.00	9.49
	Sept	351	0.00	9.49
2016	Feb	37	0.00	9.49
	May[a]	9	0.06	9.49
	Sept	13	0.01	9.49

[a] Not significant; the Chi-squared test was performed for 33 months between April 2014 and December 2016 (Data are based on 388 and 150 wells monitored in treated and control watersheds, respectively).

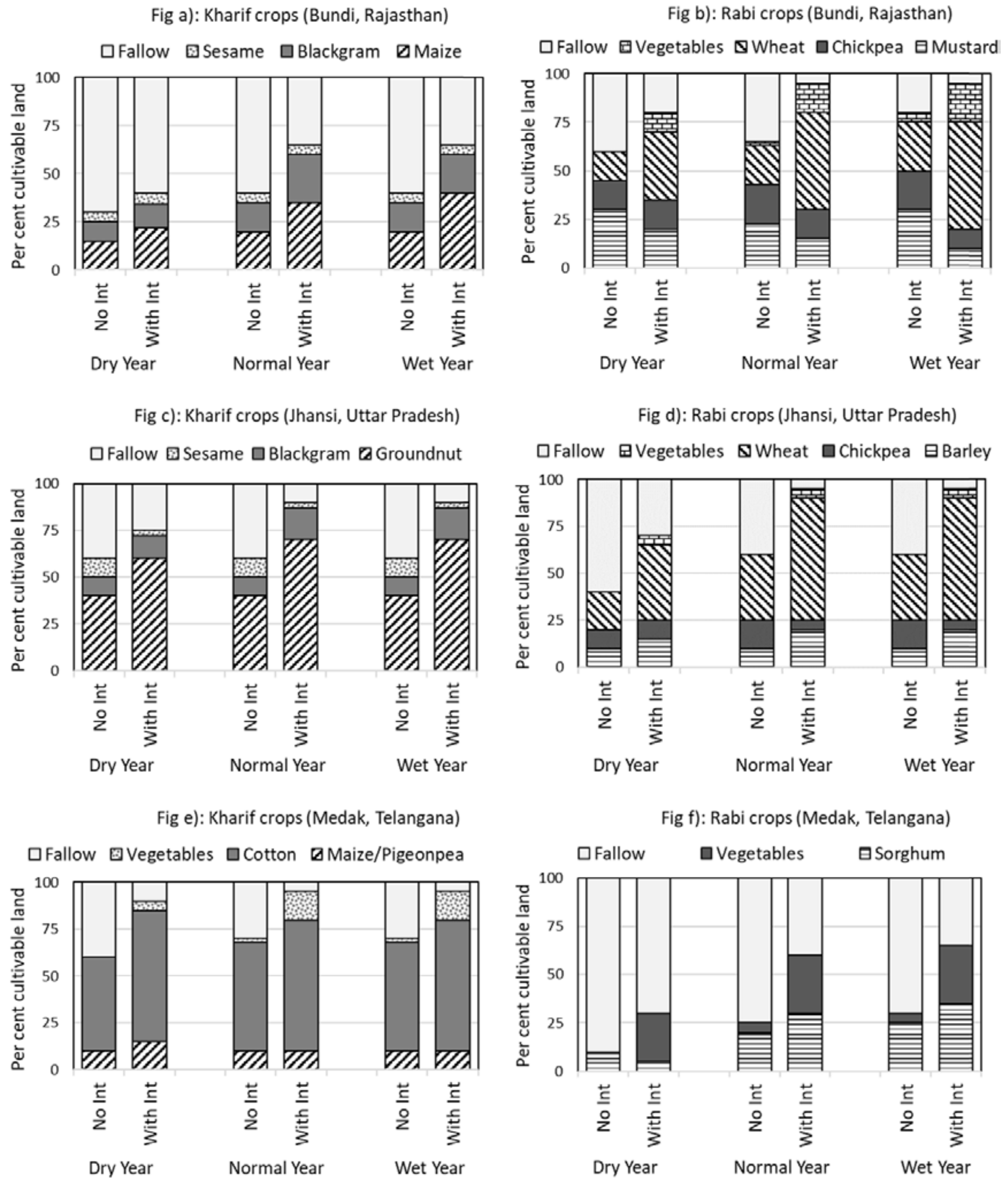

Figure 5. Change in cropping pattern due to landscape-based interventions in pilot villages of Western, Central and southern India.

chickpea declined in treated watersheds. A minimum of 25% cultivable land, especially in uplands, that was always under fallow condition due to non-availability of water had been brought into productive use and only 5% land was remained fallow during normal and wet years. On the other hand, cropping system in the Rangareddy (Telangana) project site was *kharif* dominated and has also benefited with the improved availability of groundwater. Farmers started cultivating high-value vegetable crops during the monsoon and post-monsoon season along with cotton and pigeonpea. Similarly, cultivable fallow land has declined significantly after implementing landscape-based interventions.

3.2. Bridging yield gaps through improved management practices—plot-level approach

Figure 6 shows the soil fertility status of agricultural fields in selected villages of study districts. The soil sample analysis showed that these soils are deficient in micro and secondary nutrients along with poor organic carbon status (Chander *et al* 2013, Wani *et al* 2016, 2017). For example, more than 60% of farmers' fields were found deficient in available sulphur, boron and zinc in Jhansi (Uttar Pradesh) and Tonk (Rajasthan); and 30%–60% of fields at Telangana project sites. Whereas potassium (K) deficiency was found in less than 30% of fields across study villages. Organic carbon content was found below 0.5%

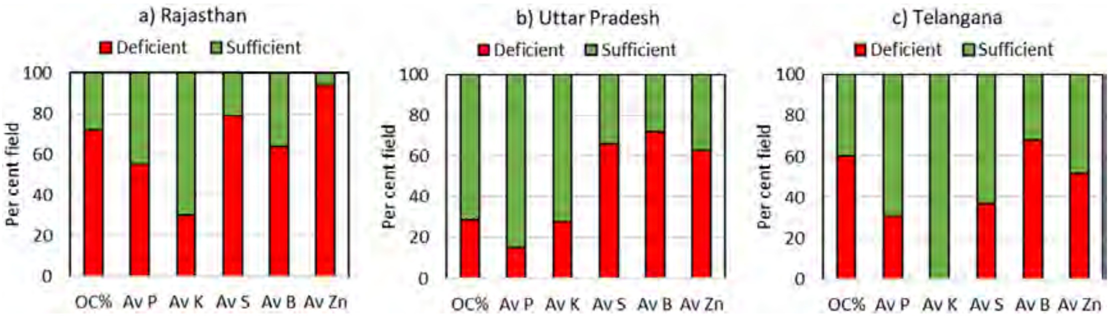

Figure 6. Nutrient deficiency status of farmers' fields in Rajasthan ($N = 178$), Uttar Pradesh ($N = 200$); Telangana ($N = 160$); Soil critical limit (OC: 0.5%; Av P: 5.0 mg kg^{-1}; Av K: 50 mg kg^{-1}; Av S: 10 mg kg^{-1}; Av B: 0.5 mg kg^{-1}; Av Zn: 0.6 mg kg^{-1}) (Sahrawat 2006, Rego *et al* 2007, Sahrawat *et al* 2007).

in 70%, 30% and 60% of fields in the Rajasthan, Uttar Pradesh and Telangana pilot sites. Poor soil organic carbon also indicates likely mineral nitrogen deficiency in these soils and therefore, requires minimum doses of nitrogen supplement in the form of organic or inorganic fertilizers.

The crop cutting studies revealed that the crop yield was sensitive to the application of micronutrients. Application of micronutrients alone helped to increase crop grain yield by 10%–30% (figure 7). However, the maximum gain yield recorded was more than 100% in some cases when the initial productivity level was very low (<300–500 kg ha^{-1}), indicating the high level of soil degradation. These initiatives helped to realize the potential of improved crop cultivars as the yield obtained in different crops was higher by 15%–30%. Some of these micronutrients activate several important metabolic reactions and play a direct role in photosynthesis and are helpful for better extraction of other nutrients from soils (Hussain *et al* 2012, Nadeema and Farooq 2019).

Farmers tend to use low yielding traditional crop cultivars due to poor awareness, non-availability of seeds of improved cultivars, and poor understanding about their suitability to their regions (Atlin *et al* 2017, Borg *et al* 2018, Singh *et al* 2020). Improved crop cultivars (including drought tolerance) along with the application of micronutrients have a compounding effect on crop yields (figure 7; table 4). With these integrated crop management practices, crop yield was significantly increased over control plots ($p < 0.05$). As prevailing crop yield levels were very low, these interventions showed higher incremental advantage and helped to bridge the yield gap. For example, the average maize yield in Tonk (Rajasthan) was 1800 kg ha^{-1}, which increased to as high as 2685 kg ha^{-1} with the application of micronutrients and 4640 kg ha^{-1} with a combination of micronutrients and improved crop cultivars. The average yield gain (difference between treated and control plots) in millets was found to be 320–420 kg ha^{-1} in response to the application of micronutrients and improved crop cultivars in Rajasthan. In the Jhansi project site, the average yield gain in groundnut, chickpea and wheat was 460 kg ha^{-1}, 700 kg ha^{-1} and 300 kg ha^{-1} respectively, with the application of micronutrients and improved crop cultivars. Similarly, the average chickpea yield in the Medak (Telangana) project site was increased from 1250 kg ha^{-1} to 1460 kg ha^{-1} with the introduction of improved cultivars.

3.3. Comparison of landscape-based vs. plot-level interventions

Figure 8 and table 5 compares the impact of plot-level and landscape-based interventions on crop intensification and net income. The implementation of landscape-based interventions helped to enhance groundwater availability additionally by 50%–100% compared to untreated condition, which made it possible for farmers to convert their cultivable fallow lands into productive agricultural land. Whereas, no such impact was observed exclusively through the plot-level approach. A minimum of 15% of cultivable fallow land was converted into productive agriculture land with landscape-based interventions in different project sites. Agricultural production ranged from 800 to 1200 kg ha^{-1} before interventions, which increased to 1500–2000 kg ha^{-1} with the introduction of plot-level interventions i.e. improved crop cultivars and micronutrients. However, in landscape-based interventions, the increase was substantial (i.e. 3500–5000 kg ha^{-1}), largely due to reduced risks of crop failure with availability of supplemental irrigation and also due to opportunity for taking a second crop within a year. As a result, household incomes from agriculture increased from US$ 150 to US$ 450/household/year with plot-level intervention and increased to more than US$ 700/household/year with landscape-based interventions. Similarly, water productivity in agriculture improved on an average from 0.15 to 0.30 kg m^{-3} with plot-level interventions and 0.60 kg m^{-3} with landscape-based interventions. As indicated by F statistics and post-hoc analysis, the difference in agriculture production and net income was significant between control plots vs treated plots and

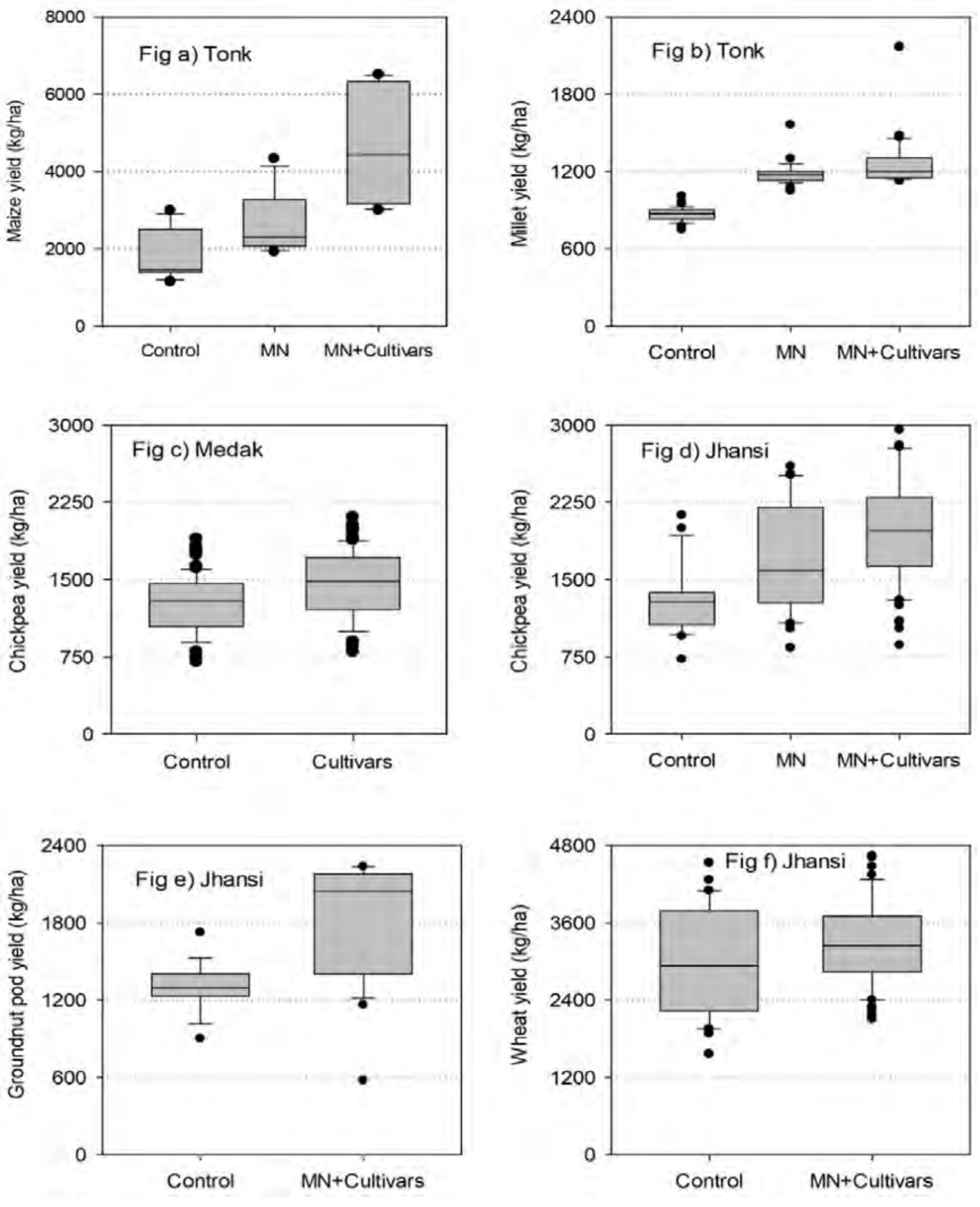

Figure 7. Impact of improved management practices on cereals, pulses and oilseeds in different environments, India. MN indicates micronutrients.

further significantly higher between landscape-based interventions vs plot-level interventions (table 5).

4. Discussion

In developing countries like India, sustainable crop intensification is required to feed the growing population, address malnutrition and fuel overall economic development (McLaughlin and Kinzelbach 2015). However, poor management of resources is one of the challenges which limits the opportunity to enhance crop intensification. Plot-level approaches to enhance crop productivity comprise a combination of improved management practices that helps to bridge the yield gap. Typically, with limited availability of moisture, their potential is not harnessed to its full capacity (Davis *et al* 2017). Landscape-based approaches first ensure moisture availability by harvesting additional runoff within the landscape in a decentralized manner (Abbasi *et al* 2019). These interventions are immensely important in the semi-arid tropical climatic conditions in which rainfall is received only for few days (30–50 rainy days) in a year. In the current climate change scenario,

Table 4. ANOVA (*F* value) showing effects of micronutrients and improved crop cultivars on crop yield (significant at $p < 0.05$).

Location	Crop	Groups	N	Mean	*p*-value[a]	*F* value	F_{Critial}
Tonk, Rajasthan	Maize	Control	61	1800	0.0003	10.24	3.68
		With MN	61	2700			
		MN + cultivars	61	4650			
	Pearl Millet	Control	71	860	0.000	217.6	3.03
		With MN	71	1180			
		MN + cultivars	71	1280			
Jhansi, Uttar Pradesh	Groundnut	Control	23	1300	0.000	21.1	4.06
		MN + cultivars	23	1760			
	Chickpea	Control	56	1300	0.000	39.4	3.05
		With MN	56	1700			
		MN + cultivars	56	2000			
	Wheat	Control	69	3000	0.002	9.80	3.91
		MN + cultivars	69	3300			
Medak, Telangana	Chickpea	Control	120	1250	0.000	28.7	3.88
		MN + cultivars	120	1460			

MN: Application of micro nutrients; Cultivars: Improved crop cultivars.

[a] Post-hoc analysis indicate significant difference in crop yield among balanced fertilizer application and improved crop cultivars at all the project sites in different crops.

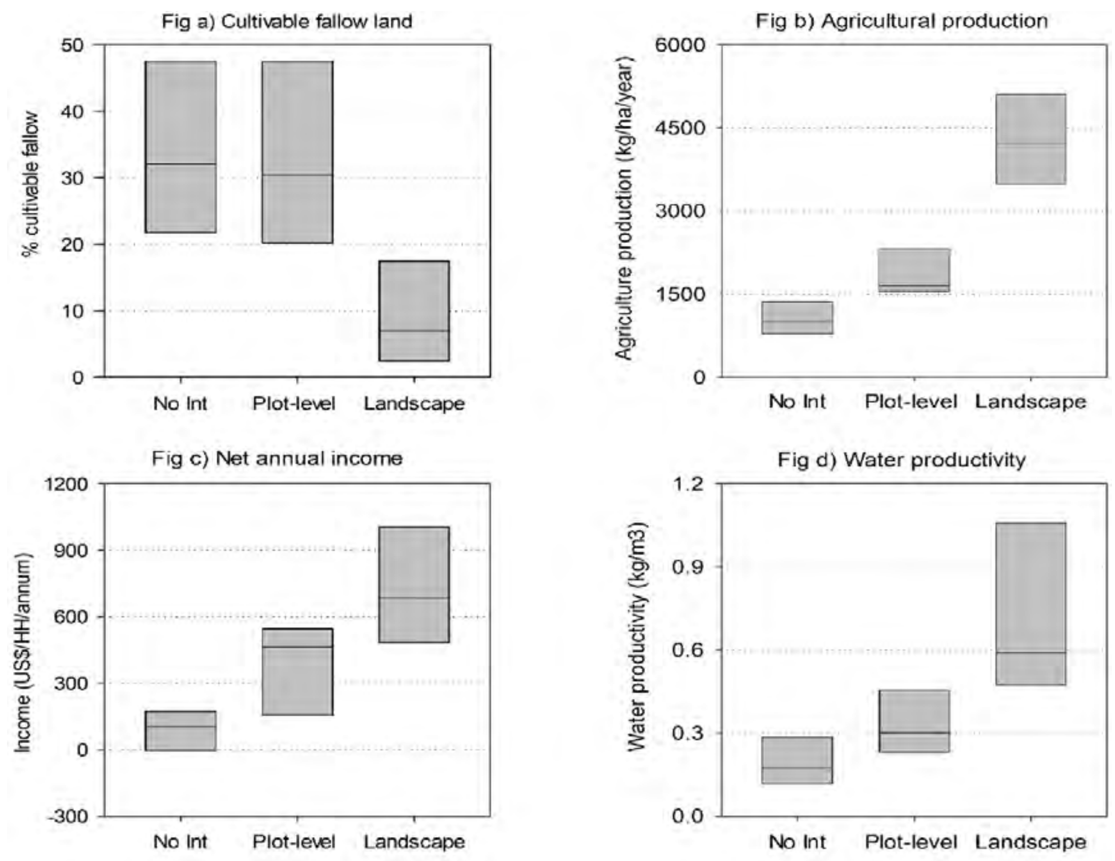

Figure 8. Comparing the impact of plot level based and landscape-based interventions on crop intensification (a) and (b), income (c) and water productivity (d).

extreme weather events are occurring more frequently across the world and the drylands of semi-arid tropics are especially affected (Chadwick *et al* 2016, Tabari 2020). Landscape-based approaches enhance residue soil moisture and strengthen groundwater availability (Meter *et al* 2014, 2016, Mandal *et al* 2020). Groundwater recharge takes place mainly during normal and wet years and may help to sustain the ecosystem even up to two consecutive years (Karlberg *et al* 2015, Garg *et al* 2020, Singh *et al* 2021). Unlike the surface storage system, which is prone to loss due to high evaporative demand (8–12 mm d^{-1}) especially

Table 5. ANOVA (*F* value) showing effects of different technologies on crop production, net income and water availability (significant at $p < 0.05$).

SN	Parameter	Treated with landscape-based interventions	Treated with plot-level interventions	Untreated/ Control plots	*F* value	F_{crit}	*p*-value[a]	No. of samples (N)
A	Rajasthan							
(i)	Crop production (kg ha yr^{-1})	5200	1658	1065	24.6	3.9	0.002	865
(ii)	Net income (US$/HH/year)	1051	56	−25	11.6	3.8	0.000	212
B	Uttar Pradesh							
(i)	Crop production (kg ha yr^{-1})	3620	1650	967	28.5	3.8	0.001	1420
(ii)	Net income (US$/HH/year)	509	452	181	9.9	3.8	0.02	417
C	Telangana							
(i)	Crop production (kg ha yr^{-1})	3450	1520	720	18.5	3.8	0.000	1086
(ii)	Net income (US$/HH/year)	862	572	57	8.9	3.8	0.03	254

[a] Post-hoc analysis indicate significant difference in landscape-based and plot-level interventions in terms of crop production and net income in all the project sites.

in summer, storing the equivalent amount of water in shallow aquifers preserves it for a longer period. Moreover, the surface water at downstream locations provides services only to a limited group of farmers, which often leads to conflict among stakeholders. In surface irrigation system, small holders and upland farmers were benefited least and found largely dependent on resource rich farmers for buying the water (Ajaz *et al*, 2019, Bajaj *et al* 2022). In contrast, the decentralized approach of groundwater recharge addresses larger groups of farmers including small and marginal farmer in an equitable manner. In these regions, groundwater is one of the reliable sources of freshwater as it is available on demand unlike surface water, which depends on predefined schedules and requires heavy investment in infrastructure (large dams and canal networks). In these areas, with innovation in pumping technologies, even marginal and small farmers can also access groundwater.

It is evident that when the water is made available, farmers were motivated to invest in new agricultural practices and explore new opportunities for crop intensification by investing in improved varieties, improved irrigation methods, farm machinery, and other farm inputs which enhanced their income and wellbeing (Ruzzante *et al* 2021). In contrast, under plot-level approach this self-motivation was relatively low as there was always uncertainty towards freshwater availability, which is the pre-requisite for crop intensification and reducing risks of crop failure. This is also one of the reasons for low adoption of improved management practices including crop cultivars especially in drylands (Cavatassi *et al* 2011, Di Falco and Bulte 2013, Ruzzante *et al* 2021); hence, agriculture growth is stagnant. Adoption of sustainable agriculture practices and outcomes are largely dependent on short term economic benefits (Piñeiro *et al* 2020). This is evident that agriculture production was about 1000 kg ha yr^{-1} which increased to 1500 kg ha yr^{-1} by introduction of plot-level initiatives, but under landscape-based interventions it increased to 3500 kg ha yr^{-1}. The net water consumption under the non-intervention stage was about 60% of the rainfall received in the respective ecologies. Whereas, with landscape-based interventions, an additional 10%–15% of rainfall was harvested in terms of soil moisture and groundwater recharge, resulting in increased production at least by three times. This phenomenon was defined by the vapour shift concept outlined by Rockström (2003). A significant amount of water from fallow lands (either seasonal or permanent fallow), which is lost as non-productive evaporation under pre- or non-intervention stage, has shifted to productive transpiration. With this approach, more than 80% of farmers benefited in the respective project locations. However, we realized that there is a trade-off between upstream development and downstream water availability, but it is always not negative (Garg *et al* 2020). Upstream development on the one hand reduces 40%–50% of freshwater availability in normal years, but at the same time it also controls floods and land degradation downstream during wet years (Garg *et al* 2021). During dry years, the generated runoff, however, is not sufficient to meet the water demand upstream and the downstream ecosystem as well, which should not be a concern. The base flow availability which has reduced significantly in last 3–4 decades in drylands and most of the perennial rivers of semi-arid tropics became seasonal (Sabzi *et al* 2019, Gerten *et al* 2020, Jägermeyr 2020), and the landscape-based approach provides an opportunity to rejuvenate the base flow with increased green cover and infiltrating more water into the soil.

The results from the plot-level approach showed positive impact in terms of enhanced productivity and knowledge of improved management practices among the community. However, these impacts are still limited to surplus production and achieving income security especially for small and marginal households that have less than 2 ha land area. Particularly during dry years, the net benefits accrued from plot-level interventions were so minimal and the impact of extreme events largely forced farmers to invest all their earnings to secure their livelihoods and they were found to be under the poverty trap (Hallegatte and Rozenberg 2017, Barbier and Hochard 2018, Marotzke *et al* 2020). In contrast, landscape-based interventions build system-level resilience against such shocks by resource creation, crop intensification and productivity enhancement (Singh *et al* 2014, Garg *et al* 2020). Even during dry years, farmers were able to harvest higher yields compared to their counterparts in untreated watersheds. Other than the direct benefits, landscape-based interventions also supported allied sectors such as livestock and water security for domestic uses (not discussed in this paper), which is one of the important challenges faced by the communities in rural areas of developing countries. With technological advancements in the areas of monitoring and evaluation, it has become possible to capture impact more accurately. It is important to put similar efforts for different agro-ecological regions to bridge the knowledge gap and to facilitate informed decisions.

The lessons of this study will be helpful to multiple stakeholders, particularly those seeking to achieve United Nations Sustainable Development Goals, as they inform the design of appropriate guidelines to promote integrated landscape approach towards addressing challenges of social wellbeing together with environmental sustainability. Policy makers should combine the results presented in this study with site-specific information to promote integration of landscape-based resource management and plot level technologies. Implementation will require a multi-disciplinary approach and extensive capacity and awareness building to address socio-economic and environmental trade-offs facing people and nature in complex dryland systems.

5. Conclusions

This paper has compared the benefits of landscape-based approach over those accrued from a plot-level approach by examining examples from three paired initiatives undertaken since 1999. The landscape-based approach was found superior in terms of water resource creation, which translated into sustainable crop intensification, increased production, and household income over the plot-level interventions in semi-arid tropics. The total production and income accrued with landscape-based management approaches, even during extreme years, were much higher than those achieved during favorable years in plot-level approaches. This study also recommends that the plot-level approach should be converged with landscape-based initiatives for maximizing the benefits and achieving sustainability. These findings have important implications for the type and scale of measures that should be implemented at various scales by stakeholders, and which should be supported by government policy interventions. They provide important examples of practice that are suitable for deployment in the arid and semi-arid regions of India, elsewhere in South and greater Asia, and also Africa and Australia. Improvements in water resource creation, crop intensification, production, and household incomes have the potential to target a range of different sustainable development goals, including those related to poverty, food security, health and well-being, inequality, and responsible production. Similar efforts are required to intensify monitoring in different agro-ecological regions and create science-based evidence for scaling up climatic resilient technologies.

Data availability statement

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

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