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Review

Impact of best management practices on sustainable crop production and climate resilience in smallholder farming systems of South Asia

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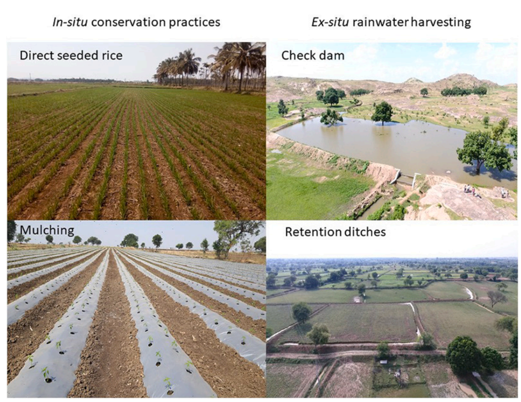
HIGHLIGHTS

- Direct seeded rice and laser land leveling interventions can reduce irrigation water requirement by 200–300 mm
- Raised bed and mulching are found helpful to conserve 50–80 mm moisture
- *Ex-situ* rainwater harvesting interventions enhanced groundwater availability by harvesting 50–150 mm surface runoff
- Integration of *in-situ* & *ex-situ* practices hold promise to bridge the yield gap while ensuring sustainable intensification

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: A host of best water and soil management practices (BMPs) hold promise in addressing water scarcity and land degradation to enable sustainable crop intensification in smallholder farming systems.
OBJECTIVE
This study quantifies the effect of BMPs on crop productivity, income, water saving and water balance components and identifies gaps for future research.
METHODS: This paper synthesizes the performance of BMPs and the existing data gap by reviewing 108 published studies from the Indian subcontinent which capture a diverse range of rainfall and cropping systems.
RESULTS AND CONCLUSIONS: In situ conservation measures helped enhance crop yields by 200–1000 kg/ha, reduced cost of cultivation and enhanced incomes by US$ 10–200/ha/year. The BMPs were helpful in enabling annual water saving in the range of 50 mm to 300 mm by either conserving residual soil moisture or saving irrigation water resulting in enhanced water productivity. Interventions such as direct seeded rice and laser land leveling were found most effective in terms of water saving and in reducing cost of cultivation. On the other hand, *ex situ* rainwater harvesting interventions helped enhance groundwater recharge by harvesting an

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additional 50–150 mm of surface runoff which helped increase crop yields, led to sustainable crop intensification and strengthened the number of ecosystem services. Most of the published literature on *in situ* conservation measures are studies that were carried out at research stations, which show promise of sustainable intensification. However, greater efforts are needed to document learnings from farmer/community scale interventions for effective scaling up. There is also a gap in data availability that hampers a clear understanding of the impact of *ex situ* rainwater harvesting interventions and ecosystem trade-offs; moreover the data available covers short periods and only covers an area of up to 10 km^2. We recommend the monitoring of long-term system-level impact indicators to realize the potential of *ex situ* rainwater harvesting interventions in a systems perspective and better grasp the ecosystem trade-offs.

SIGNIFICANCE: More importantly, the review revealed the ample scope of integrating *in situ* and *ex situ* interventions to build system-level resilience in smallholder farming systems in order to accelerate progress towards achieving the United Nations Sustainable Development Goals (SDGs).

1. Introduction

The sustainability of land and water resources is fundamental to ensure food security and livelihood opportunities for a rapidly growing population (FAO, 2020; Hogeboom et al., 2020; Mekonnen and Hoekstra, 2016). It becomes even more compelling to do so with a minimal water footprint given that the world's population is expected to touch 9.5 billion by 2050 (D'Ambrosio et al., 2020; Gerten et al., 2020). Changes in land use and growing land degradation are affecting crop yields across the globe (Montgomery, 2007; Meena et al., 2020). Global annual soil loss was estimated at about 75 billion tons in 1995, causing economic losses of about US$ 600 billion per year, which is equivalent to US$ 80 per person per year (Pimentel et al., 2010). While there is limited scope to explore available natural resources as current utilization has crossed permissible thresholds, there are opportunities to enhance resource use efficiency to meet future food and fodder demands (Rockström et al., 2009; Niu et al., 2019).

Globally, rainfed agriculture occupies 80% of the land and contributes about 60% to food production. The remaining 20% of land under irrigated agriculture supports about 40% of the food supply and contributes to food self-sufficiency in a number of developing countries (FAO, 2017). However, current resource use efficiency both in rainfed and irrigated systems is much below the achievable potential at the global level (Rockström and Falkenmark, 2015; Gerten et al., 2020). Both systems have their unique challenges (Fritz et al., 2019; Halofsky and Peterson, 2010; Poff et al., 2016; Strassburg et al., 2020; Shekhar et al., 2020; Davis et al., 2017). Rainfed systems have been experiencing physical water scarcity and land degradation (Garg et al., 2020a, 2020b; Glendenning and Vervoort, 2010; Bhattacharyya et al., 2016; Mezegebu et al., 2020; Abera et al., 2020). Therefore, a significant area of land is left fallow or underutilized due to nonavailability of supplemental irrigation (Singh et al., 2014). On the contrary, irrigated systems are subject to indiscriminate use of available resources that lead to poor resource use efficiency (Meena et al., 2019). To address these challenges, a number of promising water saving technologies and interventions (referred to as best management practices or BMPs in this paper) have been developed (Wani et al., 2017; Kumar et al., 2020; Jat et al., 2020; Garg et al., 2012; Karlberg et al., 2015; Singh et al., 2014, Singh et al., 2020a, 2020b; Abbasi et al., 2019; Meter et al., 2014; Magombeyi et al., 2018; Mandal et al., 2020; Corbeels et al., 2020; Anantha et al., 2021a, 2021b; Garg et al., 2021).

These best management practices are broadly categorized into (i) *in situ* conservation; and (ii) *ex situ* rainwater harvesting. *In situ* conservation facilitates the conservation of residual soil moisture whereas *ex situ* rainwater harvesting enhances water resource availability within the landscape. It is generally being implemented at the individual/field level whereas *ex situ* rainwater harvesting interventions are implemented both at the field and landscape levels. *In situ* conservation measures such as mulching, dry sowing of rice, zero tillage and raised beds conserve soil moisture largely from the soil's surface layers while laser land leveling facilitates the uniform distribution of soil moisture and improves irrigation use efficiency (Table 1). *Ex situ* rainwater harvesting interventions harvest surface runoff from small scale farmers' fields to *meso* scale landscape. The scale ranges from 0.1 to 10 km^2 and harvested water is available for supplemental irrigation and groundwater recharge (**Appendix 1**). Farm ponds, check dams, desilting of traditional water bodies and retention ditches are the most widely adopted *ex situ* interventions implemented across Asia and Africa (Ghosh et al., 2012; Dutta et al., 2020; Stavi et al., 2020; Wolka et al., 2020). Surface runoff generated in the field is harvested in excavated farm ponds with a capacity of 500–3000 m^3 (Malik et al., 2014; Rockström and Falkenmark, 2015; Biswas et al., 2017; Deora and Nanore, 2019; Vico et al., 2020). Moreover, the fields are divided into smaller plots with earthen bunds to control soil erosion and enhance moisture availability. Small scale field drainage structures are constructed at suitable outlets in the field for the safe disposal of excess water. These *ex situ* interventions are being promoted under various public welfare programs in developing countries such as India and Ethiopia with a focus on combating desertification and drought mitigation (Mandal et al., 2020; Abera et al., 2020; Anantha et al., 2021a, 2021b). They are also intensified at landscape scale to enhance groundwater recharge and surface water availability by harvesting surface runoff in check dams and community ponds with a storage capacity of 3000 m^3 to 50,000 m^3.

The best management practices in the drylands are gaining popularity among stakeholders as are increasingly being recognized as nature-based solutions. In the USA and Europe, these practices support ecosystem services and are often related to reducing and diffusing loads of nutrients from agriculture (Bouzouidja et al., 2021), flood mitigation

Table 1
Keywords used while retrieving the studies.

SN	Technology	Keywords searched
A	*In situ* resource conservation	
	Raised bed	Broad bed and furrow (BBF), raised bed, alternate furrow
	Zero tillage	Zero tillage, conservation agriculture, ZT-multi-crop planter
	Direct Seeded Rice (DSR)	Dry sowing, DSR, direct seeded rice
	Mulching	Mulch, plastic mulch, straw mulch, residue application
	Laser land leveling	Laser land leveling, leveling, land leveling
	Other keywords	Moisture retention, soil moisture conservation technique, conservation agriculture
B	*Ex situ* rainwater harvesting	
	Farm pond	Farm pond, sunken pit
	Traditional water bodies	Village tank, community pond, *Haveli* system
	Check dams	Check dam, earthen dam
	Retention ditches	Field bund, earthen bund, contour bund terracing, trench, staggered trench, retention ditches
	Other keywords	Water balance component, water budget, groundwater recharge, rainfall, runoff, runoff coefficient, water use efficiency, water productivity, smallholder farmers

and sediment control (Nelson et al., 2020). Given that more farmers are using agro-chemicals, these aspects of BMPs need a better understanding in the Indian context.

India is one of the fastest growing economies in the world seeking to strengthen its agriculture sector by implementing various BMPs (Everard et al., 2018). Current productivity of smallholder farmers oscillates between 0.5 t/ha and 1.5 t/ha and holds huge untapped potential that can be harnessed through BMPs. Realizing this potential, a number of public welfare programs have been undertaken in India over the last 3–4 decades, involving investments of almost US$ 2 billion/year (Mandal et al., 2020). While this is the case, there has been a gap in the systematic documentation of the benefits generated from BMPs (Glendenning and Vervoort, 2010; Glendenning et al., 2012). This paper reviews the literature on BMPs, focusing on water use for agricultural purposes in the Indian subcontinent. Its specific objectives are to: (i) quantify the effects of BMPs on crop productivity, income, water saving and water balance components; and (ii) identify current gaps in the literature and suggest directions for future research.

2. Materials and methods

The study used peer reviewed journal articles focusing on best management practices from India. The search included keywords specific to *in situ* resource conservation and *ex situ* rainwater harvesting technologies (Table 1). This literature was collected using Scopus, Thomson Reuters ISI, Science direct and Google Scholar databases. In total, 76 studies were retrieved on *in situ* resource conservation measures (Table 2) and 32 studies on *ex situ* rainwater harvesting at field and *meso* scales (**Appendix 1**; Table 2). General information/indicators for both control (traditional practice) and treated (interventions) fields from these studies, such as location details, experimental sites (research station/farmers' fields), study period, rainfall and rainfed or irrigation status were extracted.

2.1. Data analysis of in situ conservation measures

For *in situ* conservation measures, the data analysis focused on i) zero tillage, ii) raised bed, iii) direct seeded rice, iv) laser land leveling, and v) mulching. The data was analyzed for yields of major cereals (rice, wheat, maize) and pulses/oilseeds and compared between treated and control experiments. A total of 366 records were listed to analyze the impact of the measures on crop yield, cost of cultivation, water saving, water productivity and net income over the control.

Further, water productivity (WP) in treated and control plots were estimated for rainfed and irrigated systems by using Eq. (1).

$$WP\ (kg/m^3) = \frac{Grain\ yield\ (kg/ha)}{Rainfall\ (mm) + Irrigation\ applied\ (mm)} \times \frac{1}{10} \quad (1)$$

Additional water productivity was defined as the difference in water productivity between treated and control fields.

The effect of different *in situ* conservation measures on crop yield was examined by synthesizing the results of independent studies using

Table 2
List of best management practices in smallholder farming systems of South Asia.

Sl. No	Technologies	About the technology	No. of studies	References
A	***In situ* conservation measures**			
1	Mulching	Mulching is the use of any material other than soil or living vegetation that is spread over the soil to protect it from moisture loss due to evaporation. It conserves residual soil moisture and enhances resource use efficiency.	20	Sharma and Acharya, 2000; Sarkar et al., 2007; Kar and Kumar, 2007; Jat et al., 2009a, 2009b; Sharma et al., 2011; Jordán et al., 2011; Singh et al., 2011a, 2011b; Ram et al., 2013; Das et al., 2014; Ghosh et al., 2015; Prosdocimi et al., 2016; Dass and Bhattacharyya, 2017; Subrahmaniyan et al., 2018; Yadav et al., 2019; Sekhon et al., 2020; Kaur and Arora, 2019; Dutta et al., 2020; Ngangom et al., 2020; Yadav et al., 2020;
2	Dry sowing in rice	Rice seed is sown directly in the field instead of transplanting, saving significant amount of labour, energy and water inputs	23	Sharma et al., 1995; Singh et al., 2002; Bajpai and Tripathi, 2000; Hobbs et al., 2002; Tripathi, 2002; Sharma et al., 2004; Gangwar et al., 2004; Tomar et al., 2005; Tripathi et al., 2005b; Tripathi et al., 2005a; Jat et al., 2006a, 2006b; Gill et al., 2006; Singh and Singh, 2007; Jat et al., 2009a, 2009b, 2009c; Gangwar et al., 2009; Gupta and Jat, 2010; Kumar and Ladha, 2011; Gathala et al., 2011; Mishra et al., 2017; Baghel et al., 2020; Anantha et al., 2021a
3	Laser land leveling	Builds soil moisture uniformly in the field for uniform crop growth and saves irrigation water	8	Jat et al., 2009a, 2011b, 2009c; Sidhu, 2010; Jat et al., 2011a, 2011b; Naresh et al., 2014; Aryal et al., 2015; Larson et al., 2016
4	Zero/minimum tillage	Facilitates the sowing of seeds without disturbing the topsoil which holds significant amount of moisture and also reduces the cost of cultivation by saving on tillage operations	11	Singh et al., 2001; Parihar, 2004; Ram et al., 2006; Jat et al., 2006a, 2006b; Singh et al., 2008; Jat et al., 2009a, 2009b, 2009c; Saharawat et al., 2010; Sarangi et al., 2020; Tripathi et al., 1999
5	Raised bed	Facilitates the harvesting of additional rainwater in the form of soil moisture while aiding the disposal of excess runoff from the field during heavy downpours	14	Yadav et al., 2003; Jat et al., 2006a, 2006b; Chandra et al., 2007; Jat et al., 2011a, 2011b; Singh et al., 2011a, 2011b; Garg et al., 2012; Pathak et al., 2013; Jat et al., 2013; Khambalkar et al., 2014; Verma et al., 2018; Singh et al., 2018; Jat et al., 2019; Sepat et al., 2017; Anantha et al., 2021a
B	***Ex situ* rainwater harvesting**			
1	Farm ponds	Helpful for supplemental irrigation	3	Malik et al., 2014; Biswas et al., 2017; Deora and Nanore, 2019
2	Traditional water bodies	Helpful in controlling floods and soil loss at downstream sites	6	Grewal et al., 1989; Srivastava et al., 2009; Bitterman et al., 2016; Chowdhury and Behera, 2018; Reddy et al., 2018; Garg et al., 2020b
3	Check dams	Harvests excess runoff generated from fields and facilitates supplemental irrigation or helps recharge groundwater aquifers	15	Rao et al., 1996; Sur et al., 1999; Goel and Kumar, 2005; Balooni et al., 2008; Glendenning and Vervoort, 2010; Bouma et al., 2011; Garg et al., 2012; Glendenning et al., 2012; Garg and Wani, 2013; Singh et al., 2014; Karlberg et al., 2015; Chinnasamy et al., 2015; Garg et al., 2020a; Garg et al., 2021; Anantha et al., 2021b
4	Retention ditches	Facilitates groundwater recharge and controls soil loss	8	Singh, 2009; Rejani and Yadukumar, 2010; Vishnudas et al., 2012; Pathak et al., 2013; Nagdeve et al., 2021; Singh et al., 2013; Ali et al., 2017; Ali et al., 2020

descriptive statistics. Further, paired *t*-test was performed to test the level of significance of mean difference of different attributes of these interventions. A linear mixed model was performed in XLSTAT 2021 software to identify the factors (*in situ* conversation practices, rainfall regions and irrigation regimes) that influence yield gain in different crops. Eq. (2) describes the mathematical expression of the model:

$$Y = W\alpha + U\beta + \varepsilon \tag{2}$$

Where, Y is the respective outcome variables (*i.e.*, gain in crop yield), and W and U are given known and incidence matrices, respectively (Kumara et al., 2020; McLean et al., 1991).

In situ conservation measures (zero tillage, raised bed, DSR, mulching, laser leveling) were considered as fixed effects and environmental (rainfall regions) and management factors (irrigation regimes) were considered as random effects.

The model used to evaluate gain in crop yield obtained from *in situ* conservation interventions over the control plots are defined in Eq. (3):

$$Y_i = \alpha_0 + \sum \alpha_1 \text{raised bed} + \sum \alpha_2 \text{zero tillage} + \sum \alpha_3 \text{DSR} + \sum \alpha_4 \text{mulching} + \sum \alpha_5 \text{laser leveling} + \sum \beta_j \textit{Rainfall region} + \sum \beta_k \text{irrigation level} \tag{3}$$

Where, Y_i is the gain in crop yield (kg/ha); *i* represents the crop (wheat, rice, maize, pulses and oilseeds) in each iteration; α and β are the estimated coefficients of fixed and random effects.

All the explanatory variables (fixed effects) are expressed in terms of categorical values (flat bed = 1, raised bed = 2; conventional tillage = 1, zero tillage = 2; transplanted paddy = 1, DSR = 2; no mulching = 1, mulching = 2; and no leveling = 1; laser leveling = 2). Random effects such as rainfall region are categorized as <600 mm = 1, 601–800 mm = 2, 801–1100 mm = 3, >1100 mm = 4 and irrigation status was defined as rainfed/supplemental irrigation = 1, unlimited irrigation = 2.

2.2. Data analysis of ex situ rainwater harvesting

This study considered both watershed and farm scale interventions under *ex situ* rainwater harvesting measures. Landscapes treated with any *ex situ* rainwater harvesting measure was considered as a treated watershed while that without such treatments was defined as a control watershed. Indicators for *ex situ* rainwater harvesting were retrieved to analyze its impact on runoff, water table/groundwater recharge, well recovery period, change in land use and cropping system, change in irrigated area, crop yield, cropping intensity and income. Data was also segregated by normal year (rainfall ±20% of long term average), dry year (rainfall <20% of long term average) and wet year (rainfall >20% of long term average) for the respective locations as per India Meteorological Department (IMD) classification (IMD, 2010).

3. Results

3.1. Descriptive statistics of the database

Fig. 1 shows the locations of the study sites where different BMPs are practiced in India. Of the 108 studies reviewed, 86 were based on research stations and 22 on farmers' fields/community lands. Out of these 22 studies, 18 studies dealt with *ex situ* rainwater harvesting and 4 studies with *in situ* conservation. Of the 108 studies, 59 were conducted in the northern states of India, 19 in central India, 6 in the western part, 7 in eastern India and 17 in the southern states (Fig. 1). Fig. 2a describes the cumulative number of studies undertaken on select *in situ* conservation measures and Fig. 2b shows the crops studied since 1995. *In situ* conservation technologies were largely targeted in the rice-wheat cropping system. Direct seeded rice has also been the focus of researchers as rice is one of the staple cereals; it also consumes enormous amounts of water during its production cycle. Altogether, 31 research papers have analyzed the potential of DSR. The remaining papers focused on other water conservation technologies such as zero tillage (16 studies), raised bed (14), mulching (13) and laser land leveling (5) since 2010. In addition, maize and pulses and oilseeds began getting attention from 2015 onwards. It is to be noted that except for 4 studies, the rest pertaining to *in situ* conservation were undertaken at research stations under controlled conditions and on small experimental plots. Most of these technologies were also conducted under groundwater irrigation regime.

Fig. 2c shows the cumulative number of studies undertaken on *ex situ* rainwater harvesting in the last three decades. Of the 30 studies, 17 were undertaken under farmer field conditions or on community land; 8 were carried out on basin/macro scale using secondary data /survey-based instruments and simulation modeling and 5 were done at research stations under a controlled environment. Efforts are on to analyze *ex situ* rainwater harvesting interventions since 2010 as more than 80% of the studies were undertaken during this period. The review extracted information on targeted interventions implemented, location, rainfall and scale of implementation. Of the 30 studies reviewed, 19 focused on impact evaluation by measuring water balance components such as surface runoff, groundwater recharge, change in land use and increased irrigated areas following *ex situ* rainwater harvesting interventions.

3.2. Impact of in situ conservation technologies

3.2.1. Yield response

Of a total of 236 records gathered on various impact indicators (crop yield, income, water productivity and water saving) for different agroecologies and technologies, 34 records pertain to raised beds, 44 to zero tillage, 80 to DSR, 58 to mulching and 20 to laser land leveling. Fig. 3 compares the yield of different crops in control and treated fields for the respective interventions by plotting it on a 1:1 line. The values above the 1:1 line indicate a gain in crop yield due to interventions whereas values below the 1:1 line indicate yield loss. The results show that different *in situ* conservation technologies are helpful in enhancing crop yield compared to yields obtained in the control fields. The average additional crop yield obtained in maize was 690 kg/ha (SD, σ = 960 kg/ha) followed by oilseeds and pulses (300 kg/ha, σ = 240 kg/ha) and wheat (130 kg/ha, σ = 460 kg/ha). Zero tillage helped enhance crop yields in wheat and maize; led to a marginal yield increase in oilseeds and a slight reduction in rice yields over the control fields. Crop yields increased due to mulching in all cereals, oilseeds and pulses, ranging from 340 to 750 kg/ha (σ =370 kg/ha). Laser land leveling which is largely undertaken in the rice-wheat system of northern India generated additional crop yields ranging from 450 to 525 kg/ha (σ =320 kg/ha). However, yield in DSR was almost equal or slightly lower compared to that in transplanted rice. These studies show that the reduction in yield with DSR technology is largely due to increased weed infestation under aerobic field conditions.

Fig. 4 (a–d) depicts the performance of the linear mixed model in terms of predicting gains in crop yields of wheat, rice, maize, and pulses and oilseeds. Observed and predicted values are shown on a 1:1 line. Results shows that the mixed model was largely able to estimate gain in crop yields with a coefficient of determination (R^2) ranging between 0.22 and 0.31. The performance was mainly explicit in rice and pulses and oilseeds followed by wheat and maize. Table 3 further describes the coefficient estimated for fixed and random effects for different crops. The model as described in Eq. (3) was used to analyze the impact of different *in situ* conservation measures (raised bed, zero tillage, DSR, mulching and laser leveling) on gains in crop yields over the control (flat bed,

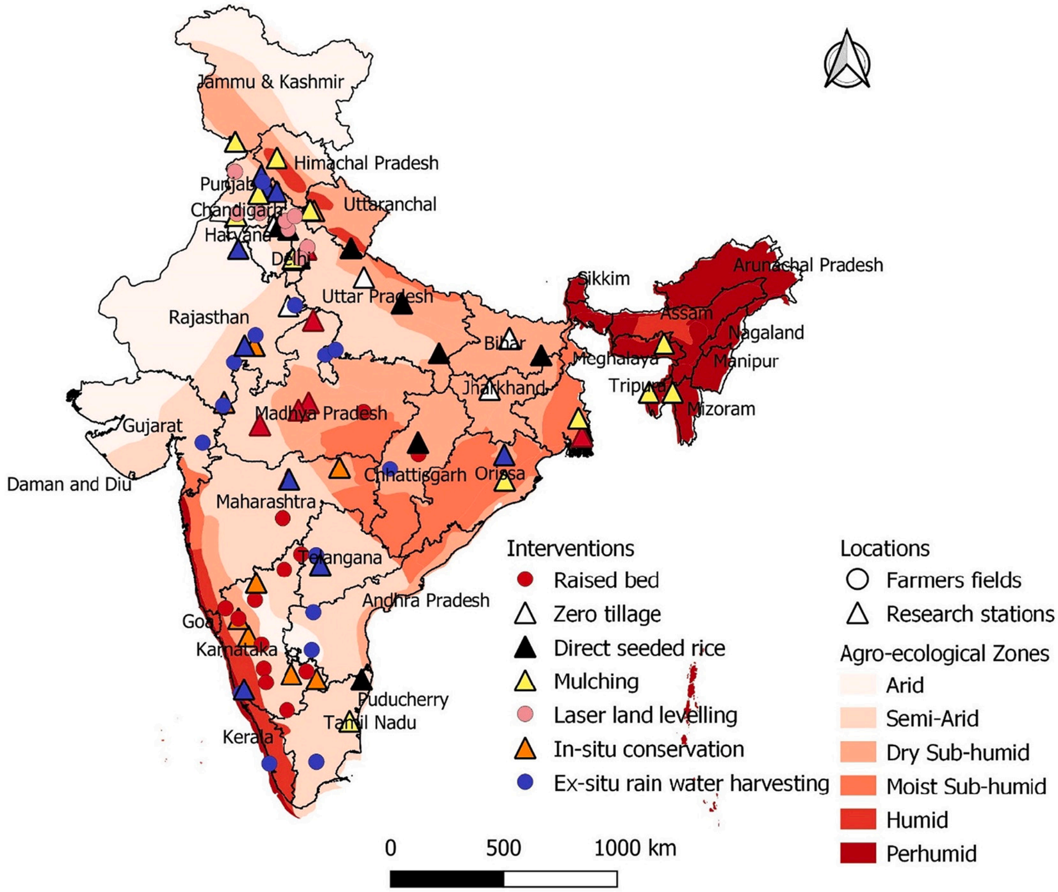

Fig. 1. Study sites of best management practices in different agro-ecological zones of India. Each mark represents one study which was included in the current review.

conventional tillage, transplanted rice, no mulch, no land leveling). The results indicate gain in crop yield of a particular variable (fixed and random) related to its corresponding reference category. The positive/negative sign of the given coefficient (Table 3) indicate the yield gain or loss in comparison to its reference category. For example, results indicate that mulching has the highest effect on yield gains in wheat (452 kg/ha loss if not mulched), followed by zero tillage (289 kg/ha gain) and land leveling (91 kg/ha loss, if not leveled) whereas gain in rice yield through land leveling was found to be 552 kg/ha. Transplanted rice and flat bed methods showed yield gains of 275 kg/ha and 185 kg/ha in rice compared to DSR and raised bed, respectively. Mulching, raised beds and zero tillage were found effective (yield gains ranging between 778 kg/ha and 1309 kg/ha) compared to their corresponding categories in maize. The yield gain in pulses and oilseeds was marginally up to 204 kg/ha due to *in situ* conservation measures. The coefficients for random effects further indicate yield gain/loss due to rainfall regions and irrigation regimes.

Fig. 5 shows the predicted means from the mixed model describing the effects of *in situ* conservation technologies in terms of gain in crop yields in major crops across different rainfall regions and irrigation regimes. Gain in wheat yield with mulching under supplemental irrigation was 548–634 kg/ha compared to 775–860 kg/ha under a full irrigation regime. Similar observations were demonstrated with zero tillage and land leveling in wheat. There was no effect of raised bed on wheat yield under supplemental irrigation while it was positive under full irrigation conditions (an additional gain of 164–250 kg/ha). The results indicate a significant difference in yield gain in wheat ($p = 0.02$), rice ($p = 0.002$) and pulses and oilseeds ($p = 0.005$) between supplemental irrigation and full irrigation regimes.

Laser land leveling was found to be the most promising intervention in rice, especially with supplemental irrigation. Gain in crop yields ranged from 645 to 1015 kg/ha under supplemental irrigation and 130–500 kg/ha with full irrigation. In addition, the rice yield gains from raised beds and DSR was found effective under supplemental irrigation and largely up to 800 mm rainfall region whereas the yield obtained under DSR and raised beds were reduced by 300–600 kg/ha compared to conventional tillage and flat beds. The difference in yield gain in maize between supplemental irrigation and full irrigation was insignificant ($p = 0.94$). This difference was also found insignificant between different rainfall regions. The impact of raised beds, zero tillage and mulching on net gain in pulses and oilseeds yields were in the range of 280–550 kg/ha under supplemental irrigation compared to 120–410 kg/ha with full irrigation.

3.2.2. *Additional income*

Gain in net income reported due to *in situ* conservation technologies over the control plots are presented on a 1:1 line in Fig. 6 (a–d). The gain in net income due to raised beds was US$ 170/ha (σ = US$ 128/ha) for maize, followed by US$ 104/ha (σ = US$ 50/ha) for oilseeds and US$ 91/ha (σ = US$ 21/ha) for wheat over the control fields. Though yield reduction was recorded in rice due to the introduction of zero tillage, net income gain was found highest in rice (US$ 226/ha, σ = US$ 251/ha) which is largely due to the reduction in cost of cultivation over

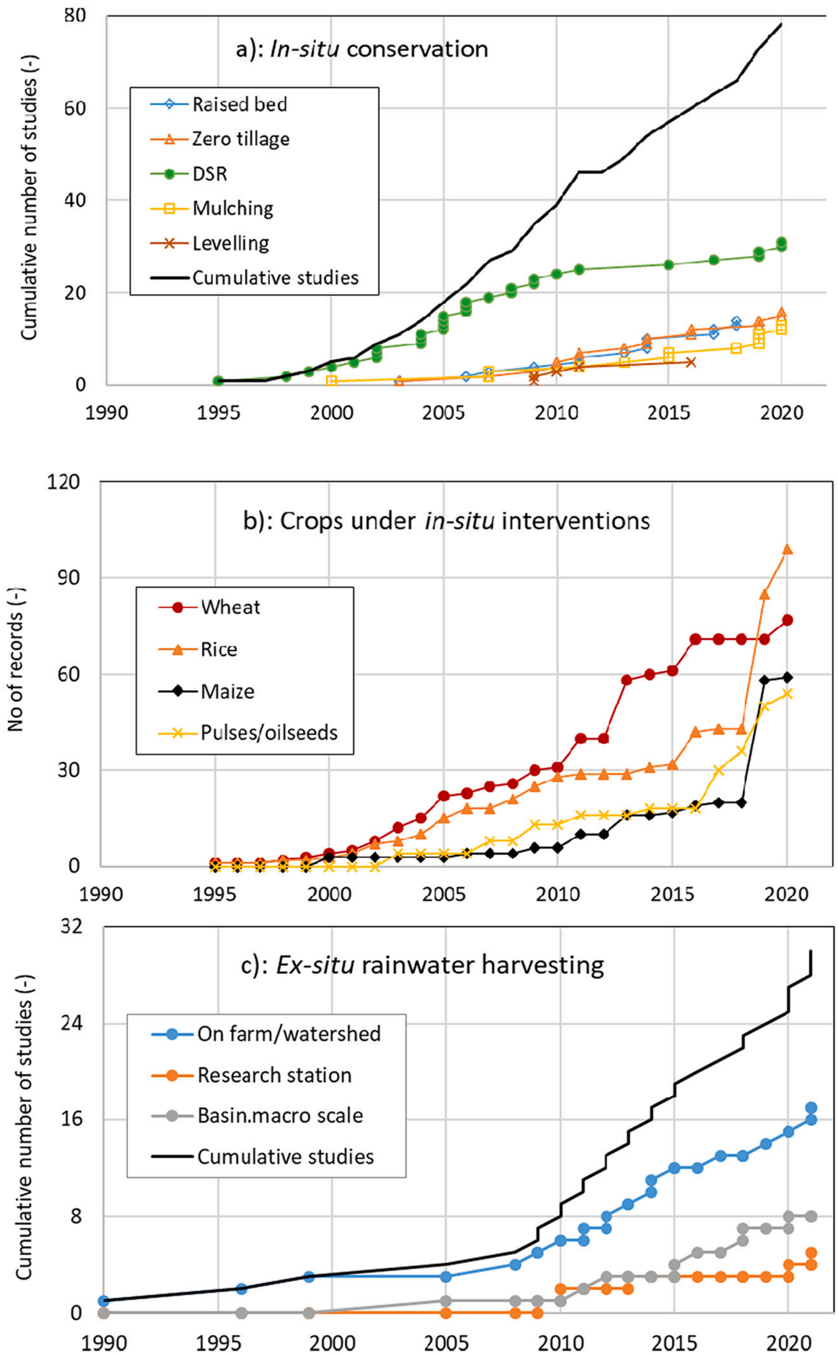

Fig. 2. Number of studies referred to on (a) *in situ* conservation; (b) crops studied and (c) *ex situ* rainwater harvesting.

transplanted rice. Net income gain due to zero tillage in wheat and maize ranged between US$ 168/ha (σ = US$ 197/ha) and US$ 173/ha (σ = US$ 147/ha). Net income gain in direct seeded rice was found to be US$ 500/ha (σ = US$ 335/ha), which is significant for marginal and small farmers.

3.2.3. *Water saving*

Results of the analysis indicate that DSR and laser land leveling are efficient in terms of water saving (Fig. 7). In DSR, frequency of irrigation declined by at least 30% compared to transplanted rice, and about 300 mm of water per crop season was saved on an average. Zero tillage which facilitates sowing without disturbing the surface soil, has helped conserve moisture from the topsoil, saving about 30 mm (10–90 mm) freshwater in a season, which is equivalent to one supplemental irrigation. However, there aren't many studies quantifying water saving through zero tillage technologies, except in rice. Similarly, raised bed technology was found helpful in conserving on an average 100 mm of water per crop season (rainfall and irrigation together) in the field. It is reported that more than 200 mm of water per year was saved due to laser land leveling in terms of reducing irrigation.

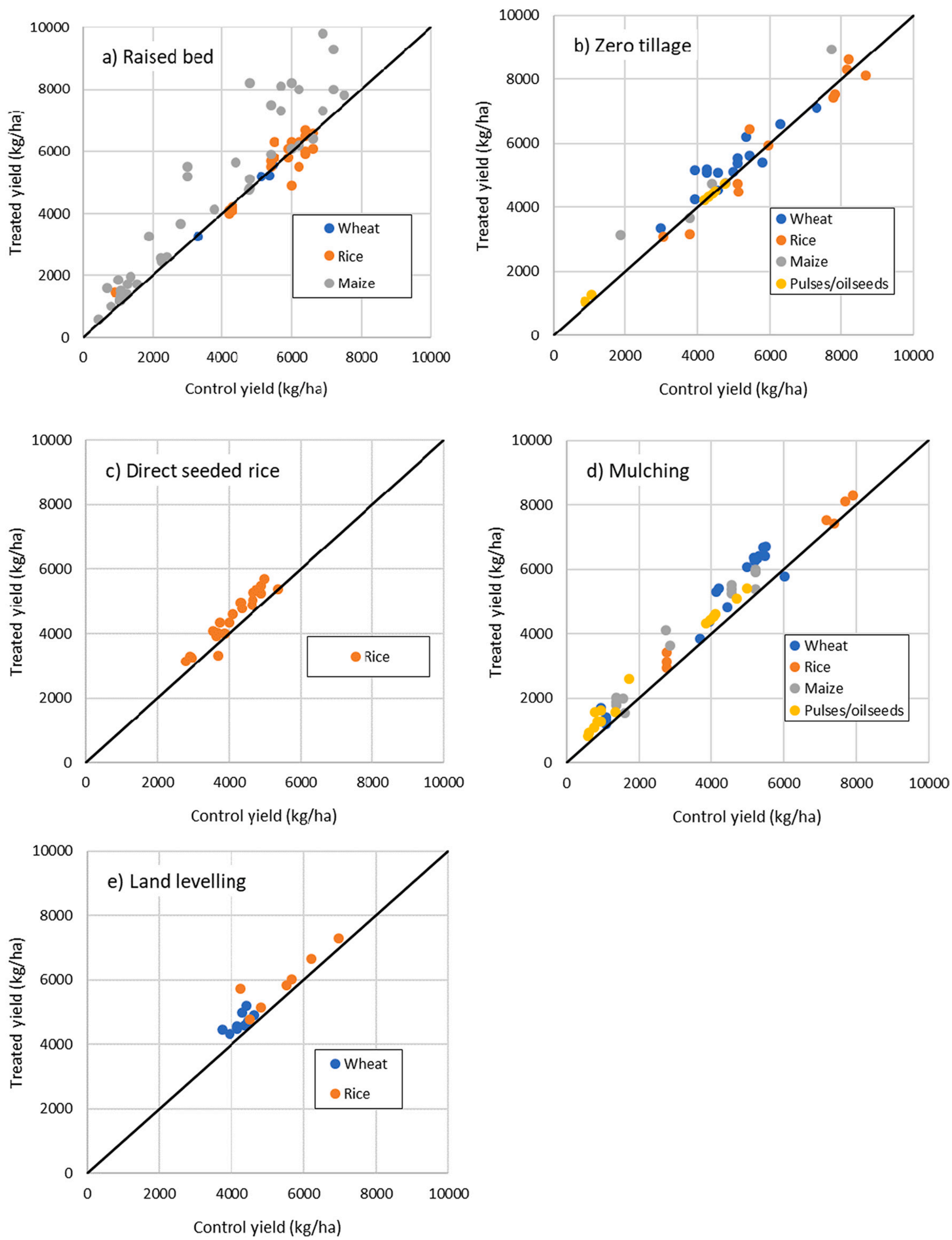

Fig. 3. Comparison of crop yields between control and treated fields (with reference to 1:1 line) for different technological treatments.

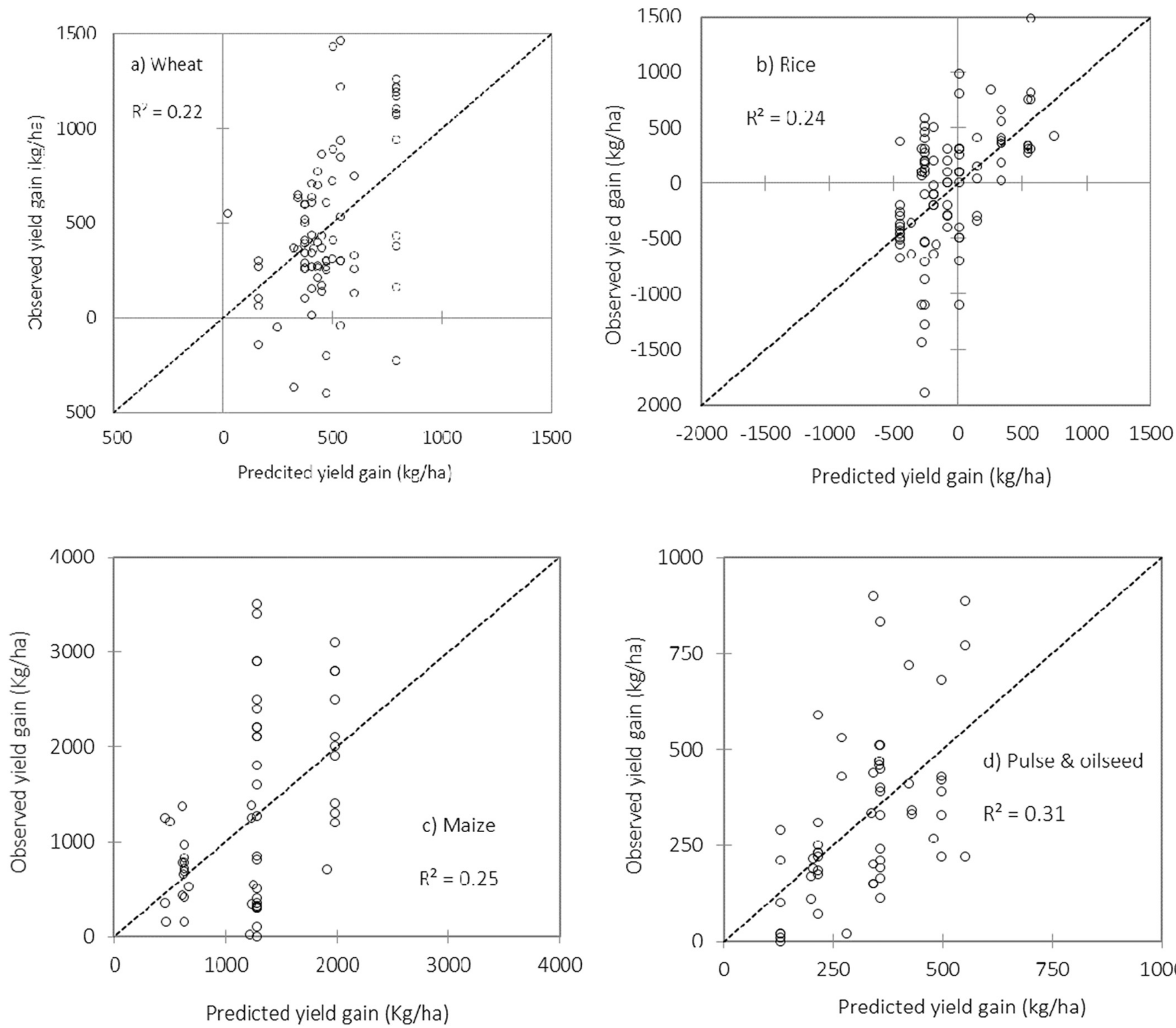

Fig. 4. Observed *vs.* predicted gain in crop yields for (a) wheat, (b) rice, (c) maize, and (d) pulses and oilseeds obtained from linear mixed modeling.

3.2.4. Water productivity

Fig. 8 explains the additional water productivity from following the technology interventions. Additional gain in water productivity was recorded in both irrigated and rainfed systems. In the irrigated system, the highest gain came from zero tillage/DSR (0.25 kg/m^3), followed by laser land leveling (0.2 kg/m^3), mulching (0.19 kg/m^3) and raised beds (0.1 kg/m^3). In the rainfed system, average gain in water productivity was found close to 0.05 kg/m^3 for different *in situ* conservation technologies. The statistical analysis indicated significant difference in gain in water productivity for fields treated with raised beds ($p = 0.004$), zero tillage ($p = 0.000$), and mulching ($p = 0.000$) under supplemental and full irrigation regimes. About 70% of the studies reported zero tillage DSR (ZT-DSR) in rice-wheat or maize-wheat cropping systems which are water intensive. As shown in Fig. 7, on an average, 200–300 mm savings in water per year resulted in improved water productivity in these cropping systems.

3.3. Impact of ex situ rainwater harvesting technologies

3.3.1. Water balance components

We identified 19 studies to understand the impact of *ex situ* rainwater harvesting interventions on change in water partitioning (Fig. 9). The studies belongs to semi-arid tropics (Fig. 1) and these areas are dependent largely on groundwater sources (shallow dug wells) for supplemental irrigation and domestic use. Fig. 9a–b shows the response of different water balance components (runoff and groundwater recharge) from 400 to 1300 mm due to year-to-year rainfall variability. As expected, runoff increased with increasing rainfall, starting from 450 to 500 mm and increased in a linear proportion. Based on the metadata, runoff coefficient estimated for control watersheds (untreated) at 600 mm, 800 mm and 1100 mm rainfall was 23%, 27% and 31%, respectively, while the runoff coefficient in treated watersheds for the same rainfall amount (600 mm, 800 mm and 1100 mm) was estimated at 6%,

Table 3
Parameters (random and fixed effects) for estimating gains in crop yield (kg/ha) in mixed modeling for different crops.

	Wheat		Rice		Maize		Pulses and oilseeds	
	Value	Standard error	Value	Standard error	Value	Standard error	Value	Standard error
Fixed effect								
Intercept	792	234	245	523	640	253	204	97
Conventional tillage	0	20	–	–	0**	10	152***	85
Zero tillage	289	167	–	–	−778**	404	0***	5
Flat bed	0**	15	188*	301	699**	315	0***	3
Raised bed	−159**	170	0*	5	0**	20	−73***	81
No mulch	−452***	132	–	–	0***	25	–	–
With mulch	0***	10	–	–	1309***	375	–	–
Without land leveling	−91	152	0*		–	–	–	–
With land leveling	0	0	552*	371	–	–	–	–
Transplanted rice	–	–	275*	329	–	–	–	–
Direct seeded rice	–	–	0*		–	–	–	–
Random effect								
RF1 < 600 mm	−39	61	0	0	−5	10	−81	107
RF2: 600–800 mm	−20	59	−199	171	0	0	56	102
RF3: 801–1100 mm	46	57	−179	176	42	36	−66	78
RF4: > 1100 mm	13	59	−369	191	−25	9	0	0
IR1: Rainfed/ Supplemental irrigation	−113	160	0	5	0	5	142	55
IR2: Irrigated	113	160	−512	259	−8	0	0	5
No of records	81		99		60		59	
R^2	0.22		0.24		0.25		0.31	

RF: Rainfall; IR: Irrigation regime.
Note: ***, ** and * indicate 1%, 5% and 10% level of significance.

12% and 17%, respectively. The analysis indicates that runoff reduced by 80–150 mm over the non-intervention condition due to *ex situ* rainwater harvesting interventions. Consequently, groundwater recharge increased by 30–100 mm compared to the control landscape depending on the location and rainfall variability (Fig. 9b). This also indicates that a fraction of surface runoff to the downstream site was retained as groundwater. Data revealed that *ex situ* rainwater harvesting interventions have increased the water table in dug wells by 3 m (2–6 m). Increased pressure head in dug wells helped reduce the well recovery period by 15 h (10−30h) on average (Table 4). In addition, water availability in dug wells increased by a minimum of 4 more months both for domestic and irrigation uses. The studies also indicate that the zone of influence in the treated watershed was found as high as 1000 m due to the constructed rainwater harvesting structures (Table 4). *Ex situ* rainwater harvesting interventions are helpful in terms of strengthening ecosystem services, such as reducing soil loss (8 t/ha) and increasing base flow period (60–70 days).

3.3.2. Crop intensification, production and income response

Our analysis showed that the area under supplemental irrigation increased on an average by 118% (70–200%) and under full irrigation by about 36% (30–60%) compared to the baseline status (Table 4). Greater cropping intensity (84%) and area under high value crops such as fodder and vegetables (12%) was also reported. Fig. 9c shows the changes in crop yields in select cereals, cotton and pulses and oilseed crops before and after the treatment. Cereal yields improved on an average from 1500 kg/ha (control) to 2500 kg/ha (treated) and cotton yields from 1000 kg/ha (control) to 1200 kg/ha (treated) and in pulses and oilseeds from 1000 kg/ha (control) to 1150 kg/ha (treated) together with annual variability and location variability. With increased crop intensification and yields, annual farm income per ha increased by US$ 382 (US$ 156–870) (Fig. 9d). The payback period (time required to recover the capital investment made on a given intervention) for *ex situ* rainwater harvesting interventions was reported to be less than 3 years, indicating high benefit-cost ratio (Table 4).

4. Discussion

4.1. Realizing the impact of in-situ resource conservation technologies: Myths vs reality

The study showed that there are advantages of *in situ* conservation technologies in terms of resource conservation and increased profitability. Direct seeded rice together with the use of zero tillage was found effective in terms of water, labour and energy saving. The current analysis showed that scaling up DSR can lead to a gradual reduction in irrigation requirements to the tune of about 200–300 mm/year. This can be helpful in saving energy and reducing the cost of cultivation in groundwater irrigated systems. Technologies such as DSR and the use of zero tillage require continuous engagement and skills to operate the equipment, calling for initial training and site-specific customized tools. In addition, integrated weed management and inter-culture operations (field operations carried out between sowing and harvesting) also needs to be addressed for successful adoption. Laser land leveling is a promising intervention in rainfed/supplemental irrigation regimes as a one-time investment (~US$ 250–300/ha) with long term benefits in terms of enhancing water use efficiency. As was demonstrated in the studies, uniform moisture availability led to reduced irrigation need in laser land leveled plots compared to relatively undulated fields which had uneven soil moisture despite irrigation. Labour requirement for irrigation also dropped in laser leveled fields due to the improved distribution efficiency of irrigation compared to control fields (Jat et al., 2009a; Jat et al., 2011a, 2011b).

Raised beds and mulching were found promising in saving about 50–80 mm/year of water by conserving residual soil moisture equivalent to 1–2 supplemental irrigations. In addition, mulching can reduce irrigation water requirement. Its impact was discernible in low rainfall zones in terms of reduced non-productive evaporation that helped meet crop water requirements. This analysis clearly demonstrates that most of the *in situ* conservation technologies are highly suitable in low to medium rainfall regions and in rainfed ecologies or areas dominated by supplemental irrigation regimes. As these areas have water scarcity due

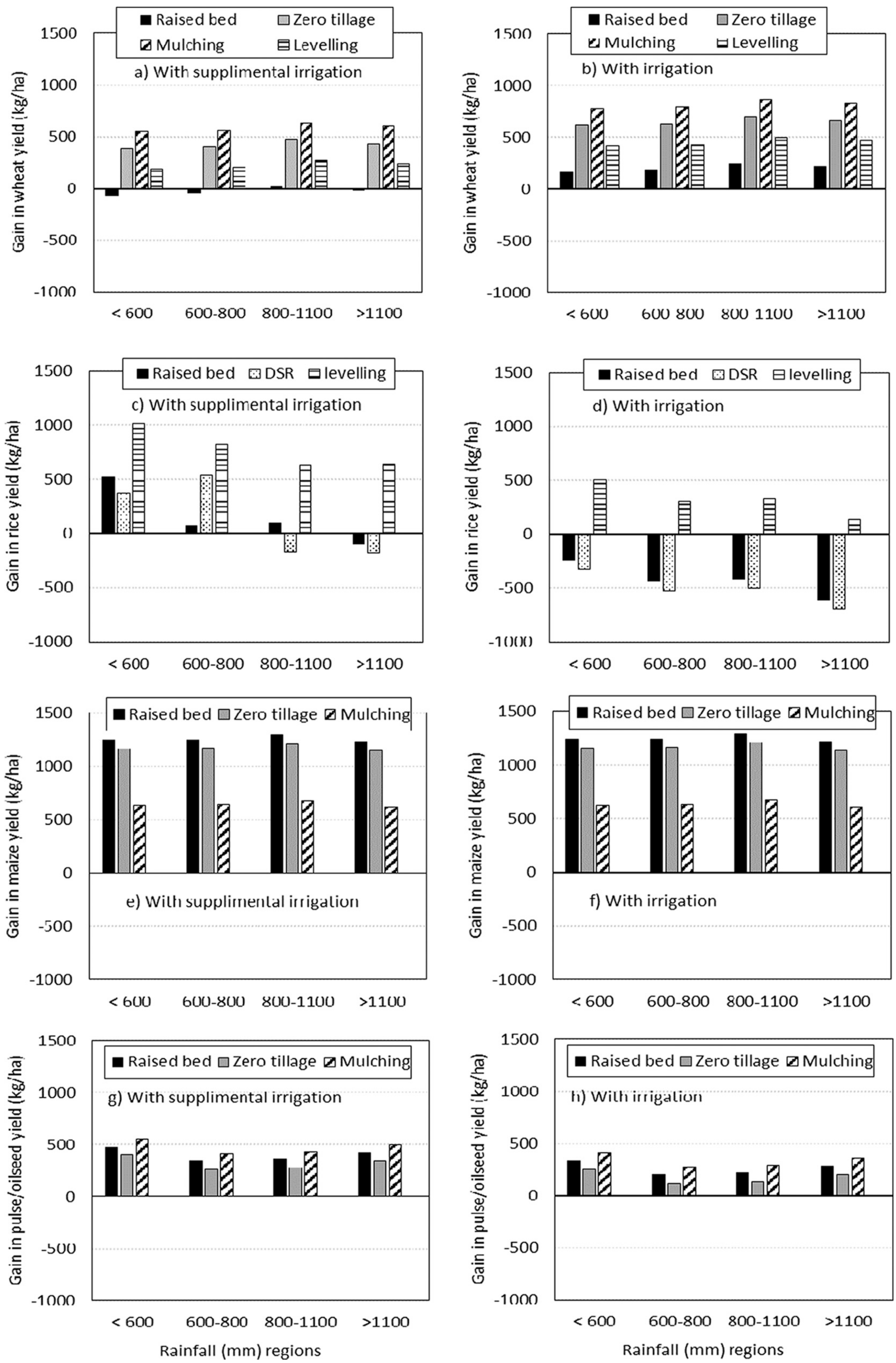

Fig. 5. Impact of different *in situ* conservation technologies on gains in crop yields in different rainfall regions and under irrigated regime (result based on mixed model).

to frequent droughts, *in situ* conservation measures help harvest additional soil moisture or protect water from non-productive evaporation, thereby increasing the longevity of residual moisture.

Based on this review, it is clear that a combination of 2–3 conservation agriculture technologies could significantly bridge yield gaps while reducing non-productive evaporation. However, the documentation of such practices has been poor, except in the northern and central part of the country, and have yet to reach most of the dryland

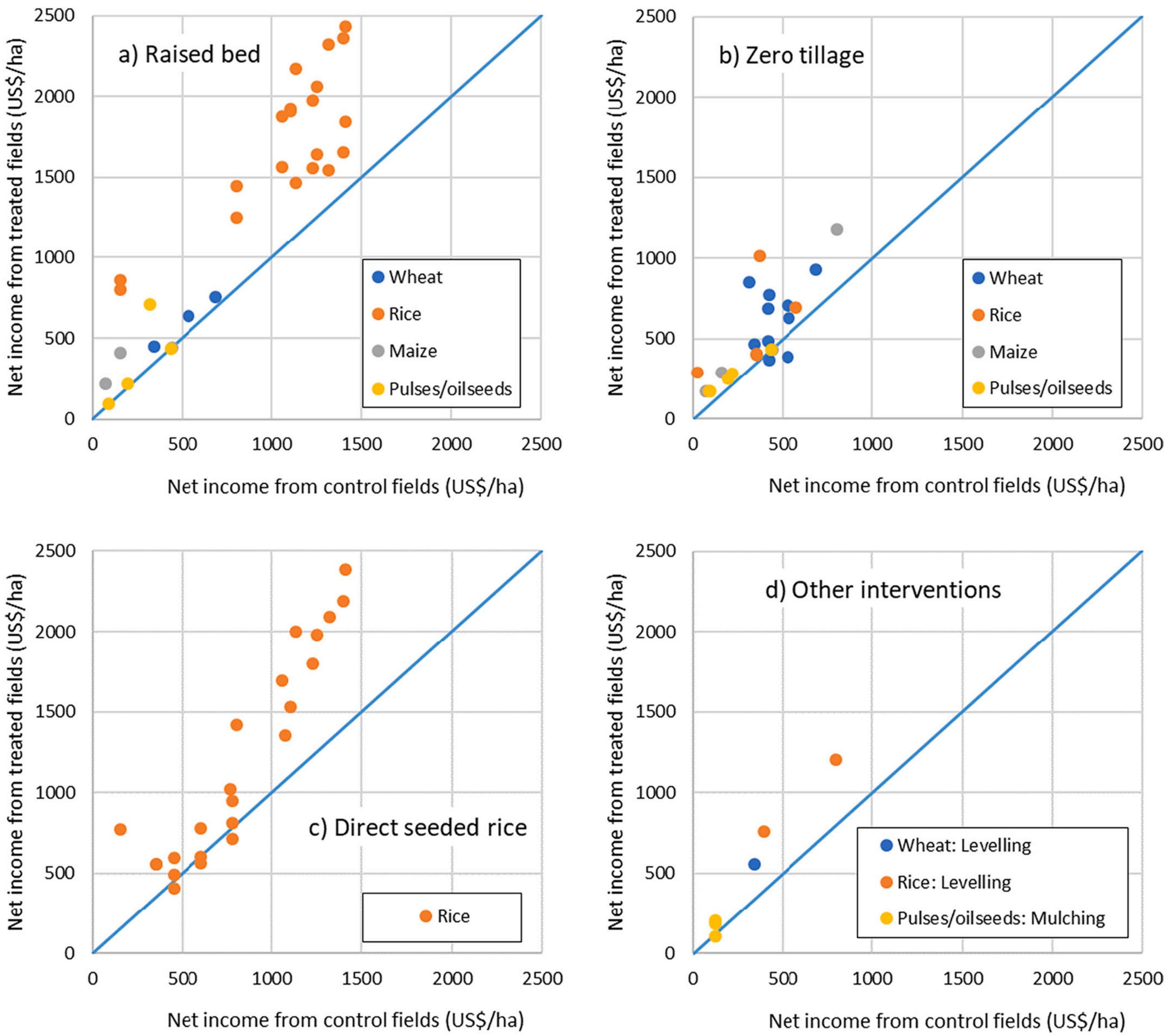

Fig. 6. A comparison of net income obtained from control and treated fields (with reference to 1:1 line) for (a) raised beds, (b) zero tillage, (c) DSR, and (d) land leveling and mulching.

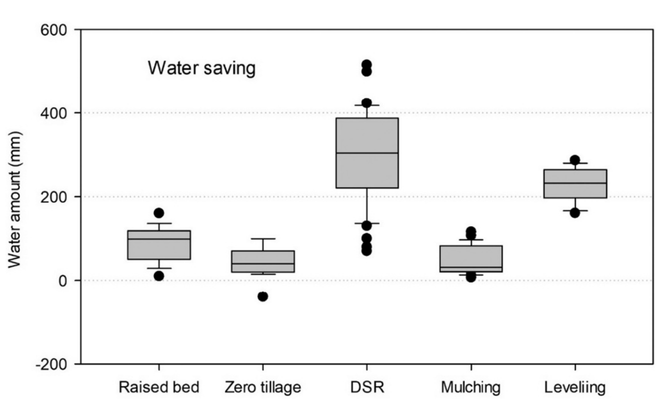

Fig. 7. Impact of *in-situ* resource conservation technologies on water saving.

areas in the country and are concentrated in parts of canal command areas (Bhan and Behera, 2014; Findlater et al., 2019).

The analysis also revealed that most of the studies attempted to assess the efficacy of *in situ* conservation technologies at research stations where experiments were undertaken on small plots under controlled conditions while many farmers in the same ecologies face a number of challenges which also require to be validated through farmer participation. The main constrains to the promotion of conservation technologies include the non-availability of machinery to suit small land holdings, competition for crop residue availability due to feeding by livestock, stubble burning, lack of skilled manpower and poor awareness of the potential benefits of the technologies (Erenstein, 2011; Bhan and Behera, 2014; Chabert and Sarthou, 2020; Pittelkow et al., 2015; Gathala et al., 2011; Singh et al., 2011a, 2011b).

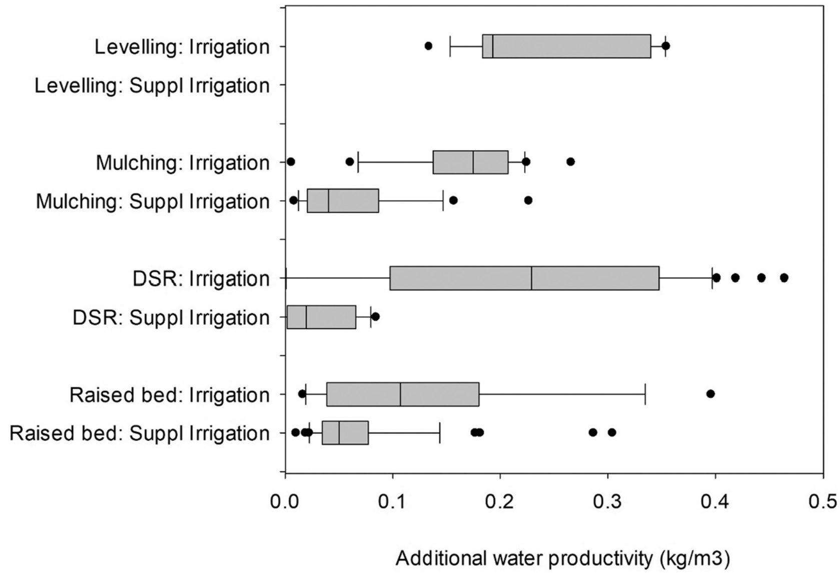

Fig. 8. Gain in water productivity following technology interventions in rainfed and irrigated systems; F-test indicates significant difference in gain in fields treated with raised beds (p = 0.004), zero tillage (p = 0.000) and mulching (p = 0.000) in rainfed and irrigated systems.

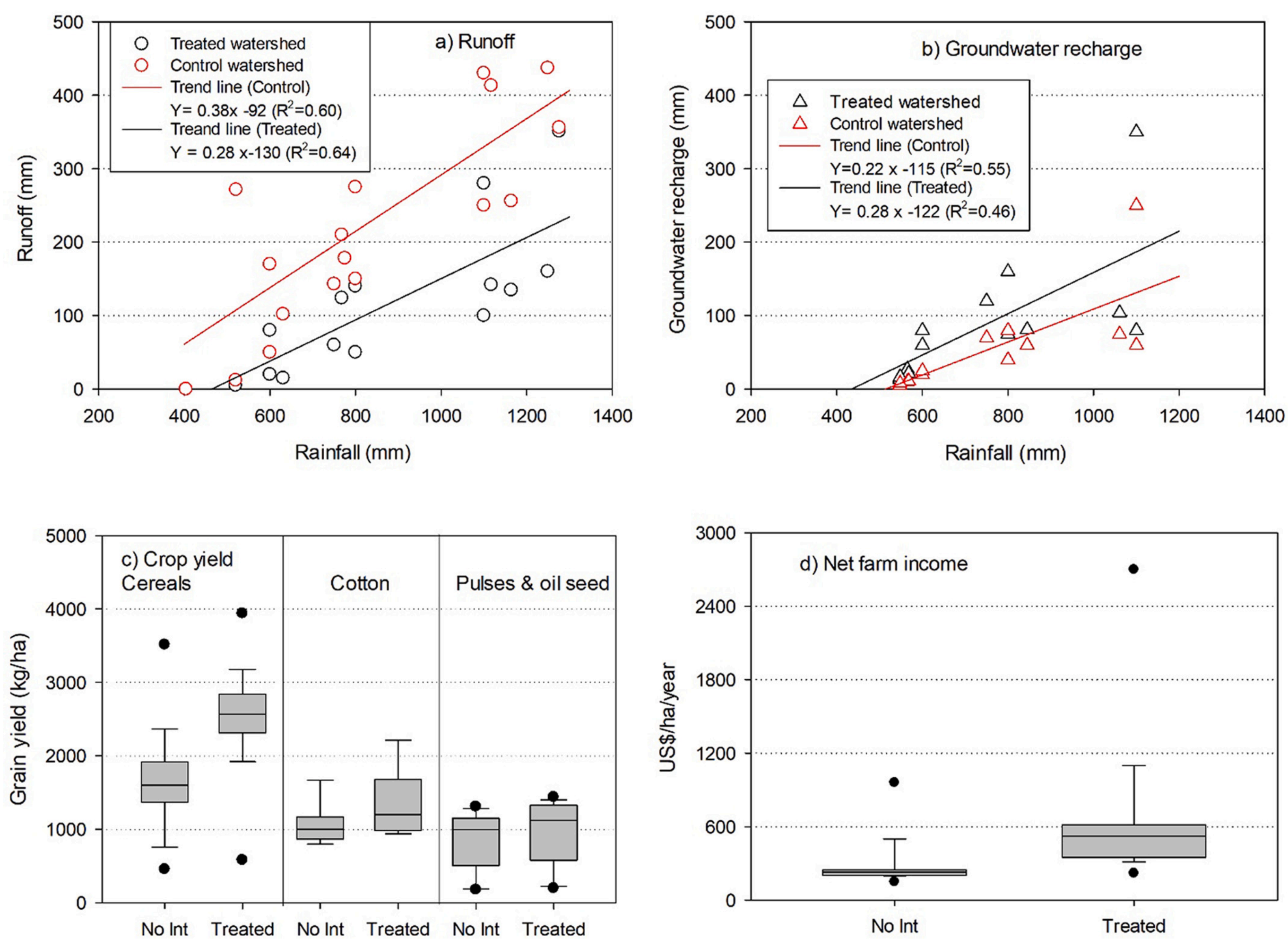

Fig. 9. Impact of various resource augmentation technologies on (a) runoff, (b) groundwater recharge, (c) crop yield, and (d) net farm income.

Table 4
Impact of *ex situ* rainwater harvesting interventions in different agro-ecologies in India.

SN	Indicators	Unit	Description	Average	Min	Max	No of studies (ref. Appendix 1)
1	Increased water table	Meter	Difference in groundwater table in shallow dug wells before and after treatment	3.2	2.5	3.5	5
2	Difference in well recovery period	Hours	Recovery period is the time required to refill the well to its steady state after pumping	15	10	30	4
3	Increased water availability in dug wells	No of months	Water availability refers to the number of months water is available for domestic and agriculture uses	4	2	6	8
4a	Increased irrigated area (1–2 supplemental irrigation)	Percent	Agricultural area supported by supplemental irrigation	118	70	200	11
4b	Increased irrigated area (full irrigation)	Percent	Agricultural area supported by full irrigation	36	30	60	6
5	Pumping period	Hours/day	Number of hours water is pumped from a well for domestic and agriculture uses	6			2
6	Increased cropping intensity	Percent	Cropping intensity is the number of times land is cultivated in a year	84	60	132	9
7	Increased area under fodder and vegetables	Percent	Area cultivated with fodder and vegetable crops	12	5	20	7
8	Increased crop yield	Kg/ha	Crop production from one hectare	892	180	1880	12
9	Cost of cultivation	US$/ha/year	Expenditure required to cultivate one hectare	175	150	200	5
10	Increased income	US$/ha/year	Net income earned from one hectare in a year after deducting the cost of cultivation from gross income	382	156	870	9
11	Drinking water availability	No of months	Number of months water is available for domestic use	8	5	12	3
12	Payback period	Years	Time required to recover the capital investment made on a given intervention	2	2	3	4
13	Reduced soil loss	T/ha	Amount of soil erosion from one hectare	8	2	15	3
14	Increased base flow period	Days	Discharge entering into stream channels from groundwater	68	60	75	3
15	Zone of influence	Meter	A zone/area in which groundwater recharge takes place due to constructed rainwater harvesting structures	900	800	1000	3

4.2. Sustainable crop intensification through ex situ rainwater harvesting interventions

The drylands experience uncertainty of resource availability and climate related challenges such as recurring droughts and floods. *Ex situ* rainwater harvesting interventions have proven to be promising risk mitigating measures that can strengthen system level resilience by enhancing groundwater availability, controlling land degradation and strengthening ecosystem services such as increasing groundwater recharge, base flow, and controlling soil erosion. Various landscape interventions facilitate the harvesting of freshwater during the wet year and support the system during dry spells and recurring dry years. *Ex situ* rainwater harvesting helped enhance water security and human well-being in a degraded dryland ecosystem. They helped swiftly recharge shallow aquifers and provided freshwater for agriculture.

Runoff and groundwater recharge are highly influenced by rainfall variability in the drylands (Garg et al., 2012; Singh et al., 2014). While watershed interventions negatively affect downstream water availability only during normal years; they assure supplemental irrigation in the uplands which are most vulnerable to mid-season drought, and to climate change. Due to poor infrastructure and degraded landscapes, upland areas in the drylands are largely owned by the poor and deprived who often struggle for food and basic amenities (Ahmed et al., 2007). Groundwater resilience can be built by diverting a fraction of surface runoff into shallow aquifers through *ex situ* rainwater harvesting interventions. During wet years, these interventions facilitate groundwater recharge to its full potential, helping build resilience to face the consequences of consecutive dry years. The analysis of *ex situ* interventions revealed that the availability of supplemental irrigation helped plan for *rabi* cultivation, and about 20% of the total area in the watershed, including a significant portion of permanent fallow was brought under cultivation (Table 4). This enhanced land and water use efficiency, food security and incomes of resource-poor communities. Such efforts towards the equitable distribution of resources like rainwater across terrains that consist of fertile lowlands and unproductive uplands can bridge income gaps within a community (Rao et al., 2017).

It was also found that *ex situ* interventions help control soil erosion and flooding in downstream areas. There could be trade-off between upstream and downstream water availability. However, it is not always negative (Garg et al., 2020a). This analysis shows that the different rainwater harvesting interventions held about 80–150 mm of water in the respective years while the rest was available to downstream users. Unlike surface irrigation projects, the community which harvests water also reaps its benefits, thereby addressing equity issues (Cochran and Ray, 2009).

4.3. Integration of in-situ conservation with ex-situ rainwater harvesting technologies

Given the fact that many parts of the country face water scarcity, there is limited scope for sustainable withdrawal of surface and groundwater, underlining the need to reconsider rainfed systems production and productivity *vis-a-vis* investments on supplemental or full scale irrigation for local and national food security (Bassi et al., 2014). Our results showed there is such potential across a range of BMPs and rainfall regions. However, since rainfed systems are subject to more variability whereas full irrigation systems require to reduce absolute water outtake, the priority should be to enable rainfed systems for farmers with conservation and supplemental irrigation.

The review showed that *in situ* conservation technologies save between 50 mm and 300 mm/year of water by conserving soil moisture or by reducing the amount of irrigation while *ex situ* rainwater harvesting technologies hint at the availability of an additional 50–150 mm/year of freshwater. Integrating *in situ* and *ex situ* technologies holds high promise for sustainable crop intensification, and can make available 100–450 mm/year of freshwater to support an additional crop or a tree-crop-livestock-based ecosystem without the additional pressure on land and water. A number of case studies during the review showed that *ex situ* rainwater harvesting interventions have transformed degraded ecosystems and farmer livelihoods into productive ecosystems (Karlberg et al., 2015; Singh et al., 2014; Garg et al., 2012; Garg et al., 2020a; Garg et al., 2021). A significant amount of residual soil moisture, especially in fallow cultivable areas, that is lost to non-productive evaporation can be converted into productive transpiration by integrating both these technologies (Rockström, 2003; Gupta et al., 2021; Anantha et al., 2021a). Nearly 30–40% of cultivable area is left fallow either in *kharif* or *rabi* seasons in Uttar Pradesh, Madhya Pradesh, Bihar, Chhattisgarh, Jharkhand, and Odisha due to scarcity of water despite rainfall ranging from 800 to 1400 mm/year, of which 80–85% occurs between June and October (Kumar et al., 2019). Uplands in these regions experience high water scarcity as a significant amount of surface runoff is drained out to downstream areas (Palchaudhuri and Biswas, 2013; Basu et al., 2015; Chowdhury and Behera, 2018; Rao et al., 2020; Mohanty et al., 2020). At the same time, downstream areas face floods and waterlogged conditions during the rainy season. The introduction and adoption of both resource augmentation and conservation technologies have immense potential for sustainable crop intensification. Due to high rainfall and high runoff coefficient (30–60%), harvesting a fraction of the surface runoff (*e.g.*, 50–150 mm/year) will be helpful for both upstream and downstream ecologies.

4.4. Gaps in database and future research needs

The current analysis shows that *in situ* conservation technologies have focused mostly on production aspects, with missing links to ecosystem services such as controlling surface runoff, enhancing base flow and groundwater recharge. These studies were largely undertaken on a plot scale at research stations; therefore their impact on large farmers' fields is not known. Data on water balance components, especially surface runoff, infiltration behavior, carbon sequestration and net consumptive water use too are missing. While the states of Punjab, Haryana and parts of Uttar Pradesh are promoting laser land leveling, zero tillage and DSR methods as part of capacity building and scaling up of technology demonstrations (Jat et al., 2020), and raised beds and mulching are being adopted in different parts of the country, there is great scope to understand the benefits of *in situ* conservation technologies on biophysical, hydrological and ecosystem components as the current focus is largely on crop yield and income.

Though India has invested more than US$ 14 billion on natural resource management, especially on landscape interventions in the last four decades (Mandal et al., 2020), it is handicapped by a lack of robust data on water balance and ecosystem services generated. Based on the extensive literature search, we could only find 19 such studies in the last 3 decades that have monitored surface runoff, groundwater recharge and estimated change in land use and crop intensification. This makes gap in knowledge as landscape hydrology varies with soil type, rainfall, land slope, land use, cropping system and management practice. Therefore, it is imperative to invest in intensive impact monitoring by collecting data on water balance, agronomy, socioeconomics, land use, cropping system together with that on interventions and investments made.

5. Conclusions

This paper reviews peer reviewed literature on different best water management practices in different agro-ecologies of the Indian subcontinent. The published works on major *in situ* conservation technologies *i.e.*, raised bed, zero tillage, direct seeded rice, laser land leveling, and mulching, have been evaluated. Similarly, studies reporting on *ex situ* rainwater harvesting technologies on *meso* scale landscapes were analyzed. The impact on crop yield, income, water saving, water productivity and various ecosystem services was analyzed. Below are the findings of the review:

- *In situ* conservation technologies were found effective in enhancing cereal yields between 200 kg/ha and 1000 kg/ha. More than 90% of the studies showed that a water saving of 50–300 mm/year resulted in enhanced water productivity. Direct seeded rice and laser land leveling demonstrated the highest water saving among all the conservation technologies, especially in rainfed/supplemental irrigation, resulting in a decline in cost of cultivation and a gain of US$ 10–200/ha in net income. Raised beds and mulching are potential interventions for rainfed systems that can lead to conserving 50–80 mm/year of water, equivalent to 1–2 supplemental irrigations.
- *Ex situ* rainwater harvesting interventions such as farm ponds, check dams, renovation of traditional water harvesting structures and retention ditches have helped harvest 50–150 mm/year of surface runoff and facilitated groundwater recharge. It was also found that various rainwater harvesting interventions and landscape resource management interventions have helped build system level resilience, enhanced cropping intensity, crop yield and household income.
- The study identified lack of data as a major gap in both *in situ* conservation measures and *ex situ* rainwater harvesting intervention studies. Most of the studies on *in situ* conservation measures were undertaken at research stations and mostly pertained to major cereals such as rice, wheat and maize along with limited data on oilseeds and pulses. Similarly, limited studies on *ex situ* rainwater harvesting interventions were available and within a limited time period. Data monitoring needs to be strengthened both at micro and meso scale landscape to understand the ecosystem trade-offs between upstream and downstream ecologies under different rainfall, soil type and land slope conditions.
- Based on the current review, we envision a huge potential to integrate *in situ* conservation and *ex situ* rainwater harvesting technologies to address water scarcity and build system level resilience. A large part of the Indian subcontinent, especially the central and eastern parts, receive medium to high rainfall (800–2000 mm/year). However, they undergo water scarcity during post- monsoon season. Integrating both the technologies has great potential to overcome these challenges and achieve sustainable crop intensification.

While this review fills the knowledge gap in the areas of best management practices, the lacunae in information on ecosystem trade-offs and building system level resilience which require intensive data monitoring, need to be filled.

Declaration of Competing Interest

We (KH Anantha, Kaushal K Garg, Jennie Barron, Sreenath Dixit, Venkataradha A, Ramesh Singh, Anthony M Whitbread), hereby declare that there is no conflict of interest among us and partners on submitted manuscript.

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Appendix 1. Number of studies on rainwater harvesting interventions reviewed, their study focus and major biophysical and impact parameters included

SN	Interventions	State	Rainfall (mm)	Scale of analysis	Location	Study focus	Approach	Study period (years)	Biophysical and impact parameters								References
									Structure capacity	Runoff	Ground water	Land use/ cropping system	Irrigated area	Crop yield	Soil loss	Income	
1	Community reservoir	Haryana	1133	0.80 km^2	Farmer	Impact evaluation	Data monitoring	10	Y	N	Y	Y	Y	Y	N	Y	Grewal et al., 1989
2	Watershed interventions	Andhra Pradesh	654	1.43 km^2	Community watershed	Impact evaluation	Data monitoring	6	Y	Y	Y	N	Y	N	Y	N	Rao et al., 1996
3	Earthen dams	Punjab	1164	0.77 km^2	Farmer	Impact evaluation	Data monitoring	10	Y	Y	Y	Y	Y	Y	N	N	Sur et al., 1999
4	Watershed interventions	Himachal Pradesh	1500	Son catchment (1200 km^2)	Catchment	Economic analysis	Secondary data analysis	–	Y	Y	N	Y	Y	Y	N	Y	Goel and Kumar, 2005
5	Temporary check dam with stones	Kerala	3250	66 households	Farmer field	Impact evaluation	Survey	1	Y	N	N	Y	Y	Y	N	Y	Balooni et al., 2008
6	Village tank	Odisha	1400	0.23 km^2	Farmer field	Impact evaluation	Data monitoring	2	Y	Y	Y	Y	Y	Y	N	Y	Srivastava et al., 2009
7	Retention ditches (contour trenches, box trench, V-ditch)	Rajasthan	960	0.05 km^2	Research station	Impact evaluation	Data monitoring	3	N	N	N	Y	N	Y	N	N	Singh, 2009
8	Low-cost rainwater harvesting structures	Rajasthan	705	477 km^2	Community watershed	Groundwater recharge (dug wells)	Data monitoring/ modeling	2	Y	N	Y	N	N	N	N	N	Glendenning and Vervoort, 2010
9	Retention ditches (crescent bund)	Karnataka	3000	0.02 km^2	Research station	Impact evaluation	Data monitoring	7	Y	Y	Y	Y	Y	Y	Y	Y	Rejani and Yadukumar, 2010
10	Watershed interventions	Southern India	850	Krishna river basin	River basin	Upstream-downstream trade-offs	Secondary data analysis	–	N	N	N	Y	Y	Y	N	Y	Bouma et al., 2011
11	Check dams	Telangana	750	3 km^2	Community watershed	Impact evaluation	Data monitoring/ modeling	10	Y	Y	Y	Y	Y	Y	Y	–	Garg et al., 2012
12	Watershed interventions	India	700	India	National scale	Groundwater recharge/ Review	Meta-analysis	–	–	Y	Y	–	–	–	–	–	Glendenning et al., 2012
13	Retention ditches (bench terrace, earthen bunds	Kerala	3100	0.02 km^2	Farmer field	Impact evaluation	Data monitoring	1	N	N	N	N	N	N	N	N	Vishnudas et al., 2012
14	Check dams	Telangana	750	3 km^2	Community watershed	Impact evaluation	Data monitoring/ modeling	10	Y	Y	Y	Y	Y	N	N	N	Garg and Wani, 2013
15	Raised bed	Telangana	800	0.05 km^2	Research station	Impact evaluation	Data monitoring	25	N	Y	N	N	N	N	Y	N	Pathak et al., 2013
16	Check dams	Madhya Pradesh	800	8.5 km^2	Community watershed	Impact evaluation	Data monitoring	10	Y	Y	Y	Y	Y	Y	Y	Y	Singh et al., 2014

(*continued on next page*)

(*continued*)

SN	Interventions	State	Rainfall (mm)	Scale of analysis	Location	Study focus	Approach	Study period (years)	Biophysical and impact parameters								References
									Structure capacity	Runoff	Ground water	Land use/ cropping system	Irrigated area	Crop yield	Soil loss	Income	
17	Low-cost RWH structures	Madhya Pradesh	900	120 households	Farmer fields	Economic analysis	Household survey	1	N	N	Y	Y	Y	Y	N	Y	Malik et al., 2014
18	Check dams	Telangana	750	3 km^2	Community watershed	Impact evaluation	Data monitoring/ modeling	10	Y	Y	Y	Y	Y	Y	N	Y	Karlberg et al., 2015
19	Watershed interventions	Gujarat	630	State	State	Impact evaluation	Remote sensing analysis	2	Y	Y	Y	Y	Y	N	N	N	Chinnasamy et al., 2015
20	Tank system	Tamil Nadu	840	State	State	Review	Conceptual framework	–	N	N	N	N	N	N	N	N	Bitterman et al., 2016
21	Percolation tank	Madhya Pradesh	820	5.32 km^2	Farmer fields	Impact evaluation	Data monitoring	6	Y	N	Y	N	N	N	N	N	Biswas et al., 2017
22	Community ponds and tanks	West Bengal	1750	State analysis	State	Tank *vs* graoundwater availability relationship	Secondary analysis	20	Y	N	Y	Y	Y	Y	N	Y	Chowdhury and Behera, 2018
23	Ancient tanks	India		India	National scale	Review	Tank rehabilitation	–	Y	Y	Y	Y	Y	Y	N	Y	Reddy et al., 2018
24	Percolation tanks	Maharashtra	750	68 households	Farmer fields	Groundwater recharge assessment	Household survey	–	N	N	Y	Y	Y	Y	N	Y	Deora and Nanore, 2019
25	Check dams and *Haveli* renovation	Uttar Pradesh	800	11.5 km^2	Community watershed	Impact evaluation	Data monitoring	6	Y	Y	Y	Y	Y	Y	N	Y	Garg et al., 2020a
26	Tanks	Karnataka	700	Kolar district	District scale	Tank *vs* water balance	Secondary data/modeling	40	Y	Y	Y	Y	Y	N	N	N	Garg et al., 2020b
27	Retention ditches (staggered trenches)	Rajasthan	741	0.039 km^2	Mini watershed at research station	Impact evaluation	Data monitoring	10	Y	Y	N	Y	N	Y	N	N	Ali et al., 2017, 2020
28	Check dams	Rajasthan	550	48 km^2	Community watershed	Impact evaluation	Data monitoring	5	Y	Y	Y	Y	Y	Y	Y	Y	Garg et al., 2021
29	Watershed interventions	Andhra Pradesh, Chhattisgarh, Rajasthan	500–1100	10–50 km^2	Farmer fields	Impact evaluation	Household survey & modeling	1	Y	Y	Y	Y	Y	Y	Y	Y	Anantha et al., 2021b
30	Retention ditches (contour trenches)	Maharashtra	842	0.25 km^2	Research station	Impact evaluation	Data monitoring	30	Y	Y	Y	Y	N	N	N	N	Nagdeve et al., 2021

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