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Technology, infrastructure and enterprise trade-off: Strengthening smallholder farming systems in Tamil Nadu State of India for sustainable income and food security

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Abstract

The complexities of smallholder farming systems pose a challenge in demonstrating the potential benefits or risks of new technologies and policies. Using Integrated Analysis Tool, a rule-based dynamic simulation model, this study tried to improve the performance of major farming systems in the Tamil Nadu State of India. Amongst the four major farming systems *viz*. Black gram-based (BFS), Paddy-based (PFS), and Integrated Farming Systems (IFS) in Villupuram district and Dryland Farming System (DFS) in Virudhunagar district, IFS was found to be the most profitable and resilient based on their performance simulated for a 3-year rotation. Setting IFS as a benchmark, potential interventions were evaluated under other farming systems to improve their relative performance. The analysis allowed understanding the interactions in smallholder farming systems and the potential impact of interventions in a whole farm way considering the cash flows, cost intensity, and input-output trade-offs. While multi-bloom technology in black gram increased the net profit of BFS without much stress on input and labour, area expansion under rainfed groundnut incurred high expenditure. Trading-off paddy with maize and groundnut significantly increased the net profit of PFS but replacing sugarcane with tapioca and turmeric was not remunerative. Improved livestock management practices have substantially increased the net profit of DFS wherein crop yield could not be enhanced substantially without the prospects of good irrigation infrastructure. The irrigation endowed PFS has achieved 90% performance, whereas the water-starved BFS and DFS could achieve only 65% performance of IFS. We conclude that agricultural policy must not only focus on potential interventions that are profitable but also consider what is acceptable to the farmer, considering synergies and trade-offs between competing resources at the farm level.

Keywords

Smallholder farming system, whole-farm model, simulation, relative performance, sustainability

Introduction

All through India's development era, agriculture remained an engine of growth in terms of increasing diversified food production, leading exports, and earning foreign exchange; and an instrument of poverty reduction that is predominantly rural in terms of raising farm income and contributing to rural employment. It also has been a mechanism to address the widening rural-urban disparity in terms of autonomous investments, subsidies, and protection than did either industry or service sectors (World Bank, 2007). Despite many notable achievements, challenges of low agricultural productivity and profitability remain. On the one hand, structural issues persist, which are responsible for continuous fragmentation of landholdings (GoI, 2016), low and stagnant income of smallholder farmers (Chand, 2017), and an increase in farmers' distress and suicides over years (GoI, 2019). On the other hand increasing market and weather uncertainties driven by globalization and climate change respectively, pose challenges for both food security and profitability (Chakrabarty, 2016; Pingali, 2007). Land degradation owing to indiscriminate use of chemicals and poor water resource management are further challenges (Bhattacharyya et al., 2015).

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In particular, small and marginal holdings which constitute 86.21% of total land holdings are important for raising agricultural growth, food security, and livelihoods in India (GoI, 2016). Smallholder farming systems involve a range of on-farm and off-farm activities that compete for limited available resources *viz*. land, labour, water, fertilizer, feed, infrastructure, cash reserves, and income. They operate in an environment characterized by risk emanating from the market, weather, and institutions; and complex interaction among most or all of the above (Dev, 2012; McDonald et al., 2019a). A challenge for Indian agricultural policy is how to increase agricultural production to feed the growing population and simultaneously make it economically profitable for the millions of smallholder farmers who depend on it (OECD/ICRIER, 2018).

Technical solutions aimed at improving the production and/or wellbeing of smallholder farmers have often had limited success as they do not utilize the experience and expertise of the target farmers and often address a single component of what is a highly integrated production and marketing system (McDonald et al., 2019b). A practical way of dealing with farming system complexity and diversity is to artificially stratify smallholders into subsets or groups that are homogenous according to specific criteria *viz*. resource base, enterprise pattern, livelihood, and constraints (Köbrich et al., 2003). Based on the unique strengths, weaknesses, opportunities, and threats (SWOT) of the identified homogenous farming systems, appropriate technologies and policy support can be introduced to make them economically viable and environmentally sustainable (Goswami et al., 2014).

However, the interdependencies and interactions in smallholder farming systems pose a challenge in demonstrating the potential benefits or risks of new technologies and policies (McDonald et al., 2019b). Moreover, farm-level experimentation of such technologies on a large scale is a time-consuming and risky affair (Sempore et al., 2015). Whole-farm bio-economic models have been developed to capture many of the key system processes and interactions of farming systems and can be used as a tool to *ex-ante* project the impacts, trade-offs, and viability or otherwise of proposed system changes (Lisson et al., 2010).

In this milieu, this study was undertaken in the Tamil Nadu State of India during 2018 to identify the major farming systems in two agriculturally significant districts under different agro-climatic conditions, to characterize them, to establish their relative performance, and to maneouvre the low performing farming systems with potential interventions to achieve the level of the best performing one through whole-farm simulation modelling.

Materials and methods

Study area

Tamil Nadu has been divided into seven agro-climatic zones *viz.* North East, North West, West, Cauvery Delta, South, High Rainfall, and Hill based on rainfall distribution, irrigation pattern, soil characteristics, cropping pattern, and other physical, ecological, and social characteristics including administrative divisions (GoT, 2020) (Figure 1).

Considering their significance in the State's agricultural production under contrasting agro-climatic conditions, Villupuram district from North Eastern Zone and Virudhunagar district from Southern Zone were purposively selected for the study. While more than 70% of 3 lakh ha net sown area in Villupuram is irrigated; less than 40% of 1.5 lakh ha net sown area in Virudhunagar is irrigated due to which about 1.6 lakh ha of cultivable land remains fallow. With 1100 mm annual rainfall and good irrigation infrastructure, Villupuram produces 17.38 million tonnes of cereals, pulses, oilseeds, sugarcane, and cotton throughout the year from 3.26 lakh ha, contributing 30% to the State's agricultural production. With only 650 mm annual rainfall and unsupportive irrigation infrastructure, Virudhunagar produces 0.50 million tonnes of millets, pulses, oilseeds, and cotton during *rabi* season (October to March) from 0.90 lakh ha, contributing 1% to the State's agricultural production (GoT, 2018). While groundwater is over exploited in Villupuram, the available groundwater is unsuitable for irrigation in Virudhunagar due to salinity.

Based on the first author's experience of working in these two districts (Varadan and Kumar, 2015), three blocks (sub-districts) *viz.* Mailam, Thiruvennainallur and Chinnaselam in Villupuram and two blocks *viz.* Aruppukottai and Narikudi in Virudhunagar practising different farming systems were selected for the investigation.

Data

In each of the selected blocks, a Focus Group Discussion (FGD) was conducted with around 10–15 farmers, coordinated by the Block Agricultural Officer to understand the various facets of agriculture in the locality *viz*. cropping pattern, landholding categories, rainfall pattern, irrigation infrastructure, marketing avenues, access to credit, inputs and extension services, the existence of organized associations, alternative sources of employment and constraints in farming. With this background information, 20 randomly selected farmers across different villages in each block were interviewed personally to collect data on their socio-economic status, agricultural infrastructure, cropping pattern, economics of different enterprises, access to institutional services, and constraints and opportunities in farming. In total, the sample size amounts to 100 farmers across the two study districts.

Various secondary sources *viz.* G-Return document of Department of Economics & Statistics, Tamil Nadu[1]; District Agricultural Plan developed by Tamil Nadu Agricultural University (TNAU), Coimbatore under National Agricultural Development Program (NADP)[2]; District Agricultural Contingency Plan developed by ICAR-Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad[3]; and TNAU Agritech Portal[4] were utilized to validate the primary data.

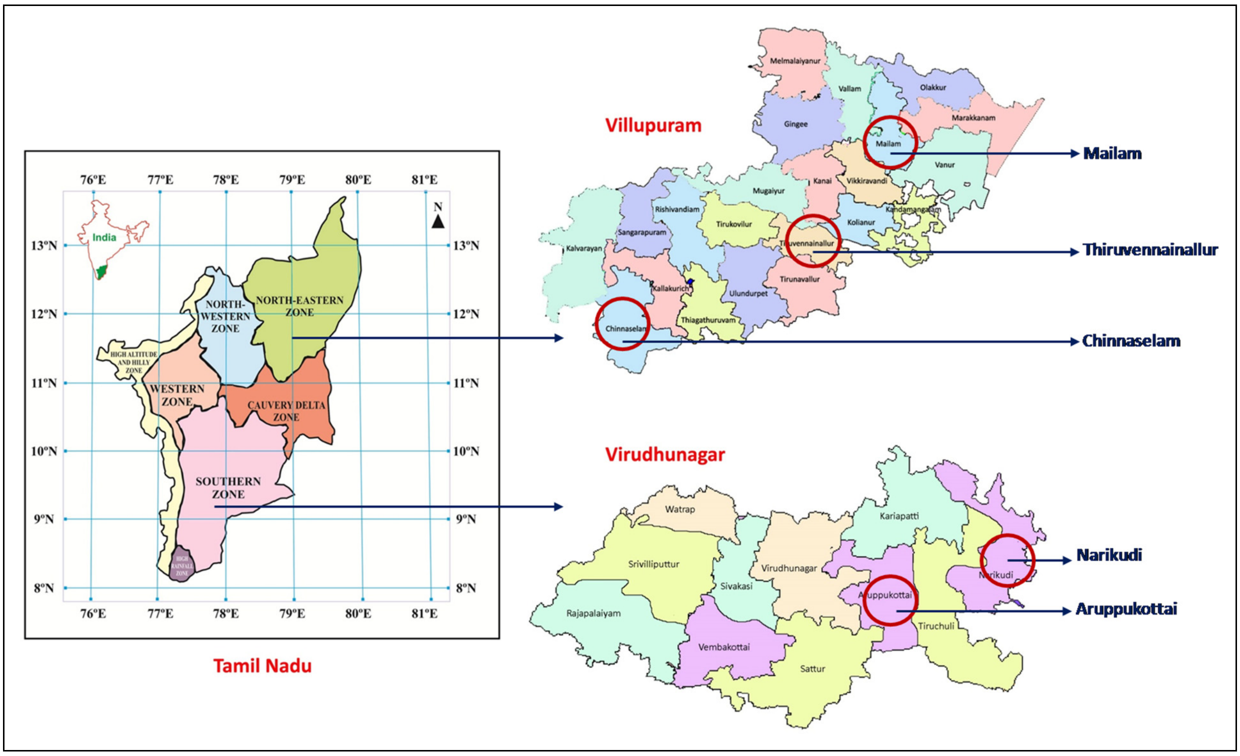

Figure 1. Geographical location of the study area.

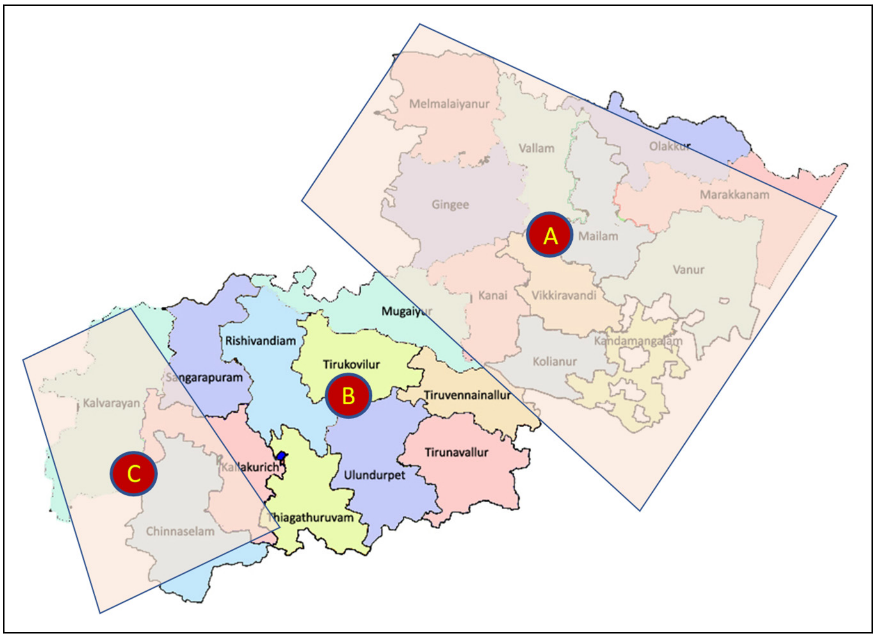

Figure 2. Geographical location of the existing farming systems in Villupuram district: A indicates Black gram-based Farming System, B indicates Paddy-based Farming System, and C indicates Integrated Farming System.

Description of existing farming systems

As discussed above, Villupuram and Virudhunagar districts were purposively selected to evaluate the contrasting farming systems. Collating data from FGDs, in-depth household surveys, and various secondary sources, three predominant farming systems were identified in Villupuram (Figure 2) and one in Virudhunagar (Figure 3).

Villupuram. Black gram-based Farming System (BFS), Paddy-based Farming System (PFS), and Integrated Farming System (IFS) were the three predominant farming systems identified across the Villupuram district, whose features are detailed as under:

BFS. This farming system is predominant in the eastern half of the Villupuram district, wherein black gram,

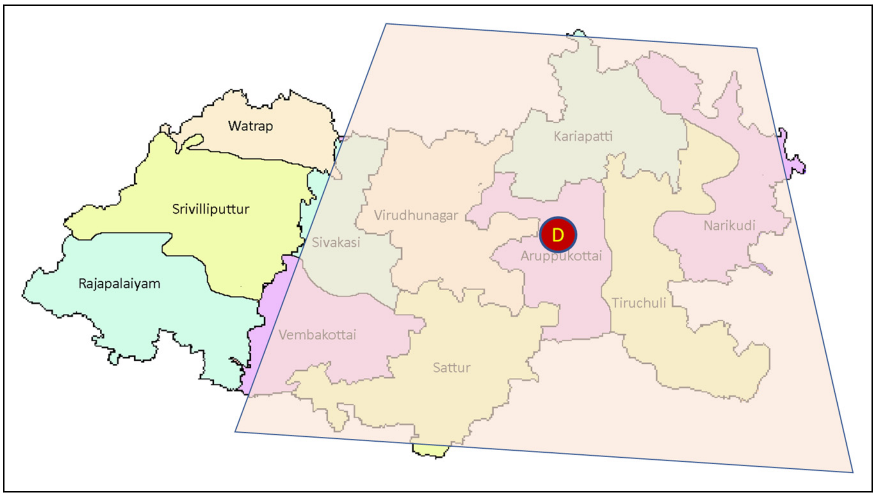

Figure 3. Geographical location of the existing farming system in Virudhunagar district: D indicates Dryland Farming System.

groundnut, and sesame are cultivated during *rabi* season and groundnut during *kharif* season (April-September). Besides, swathes of land are planted with high-density casuarina for a three-year rotation which has multiple uses *viz*. timber, board making, and pilings.

PFS. This monocropping farming system prevails all across the Villupuram district under irrigated conditions, especially in the central region. Farmers practising such a system grow three paddy crops in a year alongside sugarcane.

IFS. This diversified farming system exists in the western parts of Villupuram. Under this system, farmers grow at least five different crops in a given season and hold a variety of livestock including cow, goat, poultry, and duck; and the land is cultivated round the year with efficient irrigation infrastructures *viz*. drip, sprinkler, and rain gun. The family resides on the farm and all members engage in farming activities.

Virudhunagar. Physiographically, Virudhunagar has two distinct regions—the eastern slopes of Western Ghats in Srivilliputtur, Rajapalayam, and Watrap blocks; and the rest being black soil plains. While the agro-climate in the western part of the district is favourable to cultivate plantation crops *viz.* coconut, mango, teak, tea, and coffee, most of the district is high and dry where a diversified Dryland Farming System (DFS) is prevalent, whose features are detailed as under:

DFS. Farmers practising this system meticulously grow a range of dryland crops *viz.* major and minor millets, pulses, oilseeds, and cotton as either inter-crop, mixed crop, bund crop or sole crop mainly during *rabi* season.

Characteristics of representative farming systems

As per the landholding pattern of Tamil Nadu, 78.41% of 79.38 lakh operational holdings are marginal (<1 ha), 14.10% are small (1 to 2 ha), 5.70% are semi-medium (2 to 4 ha), 1.61% are medium (4 to 10 ha) and 0.19% are large (> 10 ha) (GoI, 2016). Thus, 98% of landholdings are smaller than 4 ha which is too small to operate and their creditworthiness is rated very poorly. That sets the limit for investment in farm assets and modern inputs that are essential for intensive farming. One advantage of such farms is that farmers pay personal attention to cultivation and use family labour which is mostly unskilled and has very little opportunity to find other jobs (Planning Commission, 2005). Considering 4 ha as an economic holding for a smallholder farming system in Tamil Nadu, a representative BFS in Villupuram holds a farm size of 3 ha in which groundnut is cultivated in 0.15 ha during *kharif* season and black gram, groundnut, and sesame are cultivated in 1.2, 0.45, and 0.15 ha respectively during *rabi* season (Table 1). An area of 1.2 ha is permanently allotted to a 3-year cycle of casuarina. Two family members mostly husband and wife share the farm operations wherein the woman manages 3 milch cows. A representative PFS in Villupuram holds a farm size of 2 ha wherein 1 ha is allotted to annual sugarcane and the other half is cultivated with paddy for three seasons. Two family members mostly husband and wife share the farm operations wherein the woman manages 3 milch cows.

A representative IFS in Villupuram holds a farm size of 3 ha in which cotton and maize are cultivated in 0.8 ha each during *kharif* season; maize, cotton, black gram, groundnut, and sesame are cultivated in 1, 0.4, 0.3, 0.2, and 0.1 ha respectively during *rabi* season; and annuals *viz*. tapioca and turmeric are cultivated in 0.8 and 0.2 ha respectively. At least 4 family members of the resident household share the farm operations and maintain 5 milch cows and 10 goats. A representative DFS in Virudhunagar holds a farm size of 3 ha which lies fallow during *kharif* season and maize, sorghum, cotton + black gram, and groundnut are grown in 0.6, 0.6, 0.6, and 0.2 ha respectively during *rabi* season. While 2 family members mostly husband and wife share the farm operations, 4 milch cows and 10 goats are managed as a supplementary enterprise.

Table 1. Characteristics of representative farming systems in Villupuram and Virudhunagar.

Particulars	BFS	PFS	IFS	DFS
Farm size (ha)	3.0	2.0	3.0	3.0
Kharif crops with area (ha)	groundnut (0.15)	paddy (1)	cotton (0.8) maize (0.8)	—
Rabi crops with area (ha)	blackgram (1.2) groundnut (0.45) sesame (0.15)	paddy (1)	maize (1) cotton (0.4) blackgram (0.3) groundnut (0.2) sesame (0.1)	maize (0.6) sorghum (0.6) cotton + blackgram (0.6) groundnut (0.2)
Summer crops with area (ha)	—	paddy (1)	—	—
Annuals with area (ha)	—	sugarcane (1)	tapioca (0.8) turmeric (0.2)	—
Perennials with area (ha)	casuarina (1.2)	—	—	—
Milch cattle (nos.)	3	3	5	4
Goat (nos.)	—	—	10	10
Family labour (nos.)	2	2	4	2

Methodology

A wide range of whole-farm models are available of which three main types emerge *viz*. a) Static linear programming models maximizing a utility function under constraints, representing the farm a combination of linear activities, either over a single year or over several years; e.g. UE-DSP (Torkamani, 2005), MIDAS (Bathgate et al., 2009), FarmDESIGN (Groot et al., 2012), b) Static simulation models, describing farm operations based on stocks and flows over a single year; e.g. Cikeda (Andrieu et al., 2012), FSSIM-Dev (Louhichi and Paloma, 2014), and c) Rule-based dynamic simulation models with decision rules representing farmers' management modes in the form of "IF conditions THEN action" rules, simulating changes in the farm-state over one or several years; e.g. Simflex (Andrieu et al., 2015), IAT (Monjardino et al., 2020), TOA-MD (Shikuku et al., 2017).

Each type of model has specific advantages and limitations (Sempore et al., 2015). Static linear programming models feature relatively strict construction principles which are too distant from the reality of farmers' decision-making process. Since such models are usually single objective oriented like profit maximization, they hold little interest for farmers who have multiple objectives. Static simulation models are useful when technological innovation is disseminated by allowing the consequences of farm results to be measured *ex-ante*. But, their limitation lies in the kind of practices taken into account in the model. Rule-based dynamic simulation models which examine the reliability of a farmer's decision-making processes in response to climatic and economic risks, allow the researcher to better identify these processes.

Hence, this study has used Integrated Analysis Tool[5] (IAT)—a rule-based dynamic simulation model which captures the key economic and biophysical processes and their interactions in the smallholder farming system to quantify the production and economic impacts of various crops, forage, and cattle improvement strategies; and to identify the most promising best-bet options for subsequent on-farm trialling (Lisson et al., 2010). The strengths of IAT are well documented by McDonald et al. (2019a). The model simulates the performance of a typical smallholder farm household over a given period *viz*. 5 to 10 years (Monjardino et al., 2020) by integrating data and outputs from three separate models: the Agricultural Production Systems Simulator (APSIM)—a crop simulation model, a livestock growth model, and a whole-farm economic model with dynamic linkages among them which enables assessing the competitiveness of a range of crop-livestock enterprises/combinations and best management strategies; and their impacts on whole household cash flows and risk management plans considering climatic variability, labour availability, landholdings, and other socio-economic constraints (Lisson et al., 2010).

IAT has largely been employed to demonstrate the impact of various plot-level crop management and farm-level enterprise interventions on income variability and household food security (Komarek et al., 2012); to assess synergies and trade-offs between alternative incremental adaptation options to climate variability under contrasting smallholder mixed farming systems (Rigolot et al., 2017); and to evaluate the implications of livestock improvement and intensification through optimizing forage production to identify strategies that increase whole-farm incomes, reduce yield gaps and mitigate risk (Komarek et al., 2015; Lisson et al., 2010; Mayberry et al., 2017).

Considering the presence of 3-year rotation casuarina in BFS, the primary data obtained from FGDs and personal interviews were fed into IAT and the model was simulated for one 3-year cycle from 2018 to 2020 to examine the relative performance of the four representative farming systems with respect to six indicators *viz.* input cost, labour cost, labour requirement, family labour utilization, fodder cost, and net profit. The relatively best performing farming system was set as a benchmark and potential interventions were designed for other farming systems so that they can achieve the performance of the best one. SWOT analysis

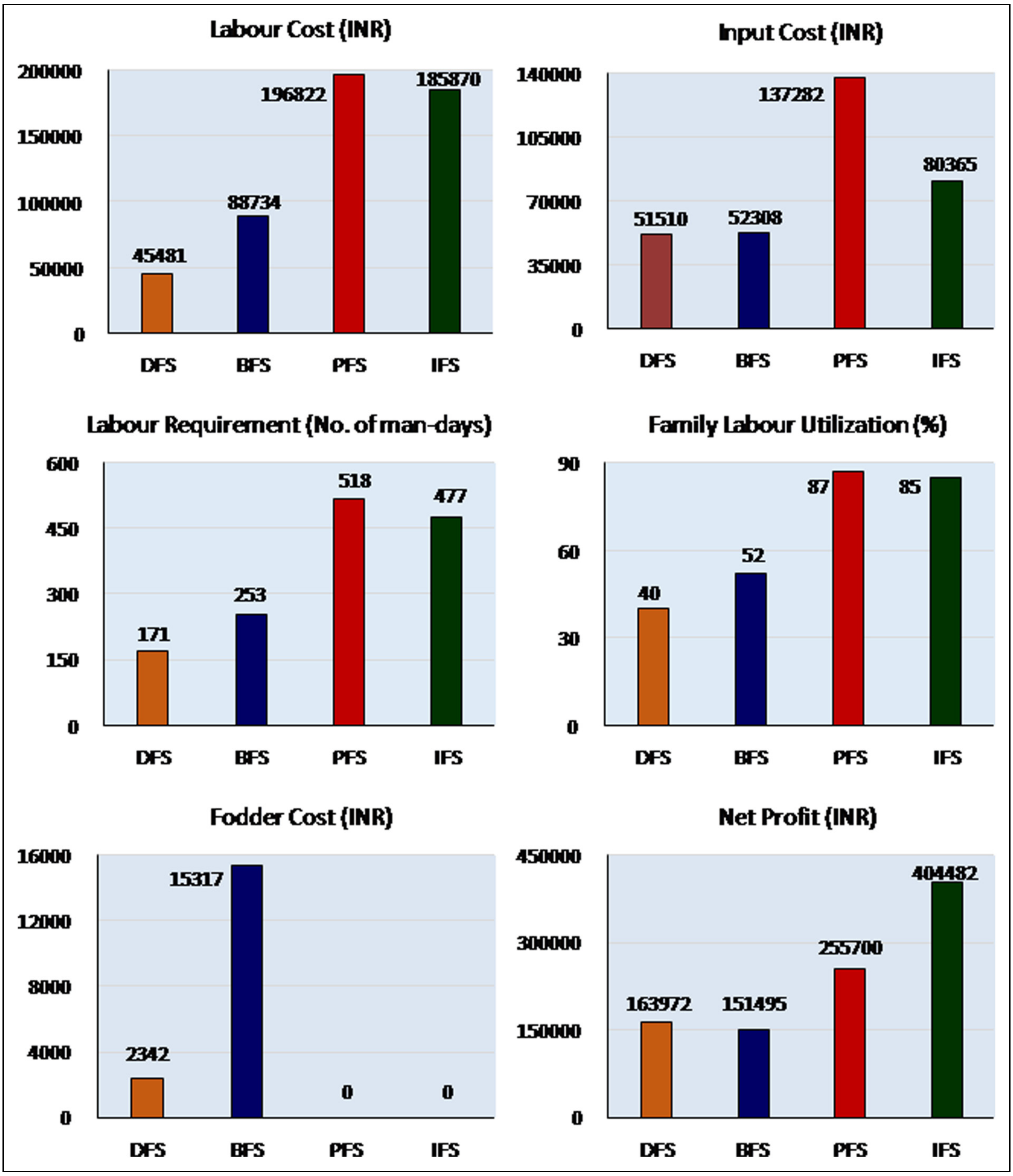

Figure 4. Relative performance of the representative farming systems in Villupuram and Virudhunagar: DFS - Dryland Farming System, BFS - Black gram-based Farming System, PFS - Paddy-based Farming System, IFS - Integrated Farming System, and 1 US Dollar (USD) = 63 Indian Rupee (INR).

was done for each of the farming systems through a participatory process before designing such interventions.

Results

The relative performance of representative farming systems

A 3 ha DFS in Virudhunagar district that cultivates maize, sorghum, cotton, black gram, and groundnut during *rabi* season with supplementary livestock of 4 cows and 10 goats incurred an expenditure of INR 45,481 and INR 51,510 per annum towards material inputs and labour respectively (Figure 4). All the farm operations generated 171 man-days which were partly fulfilled by 40% of family labour. In addition to crop stover, INR 2,342 was spent to buy fodder. After deducting the additional expenditure on interest and overheads (farm maintenance, machinery maintenance, fuel costs, insurance, taxes, electricity,

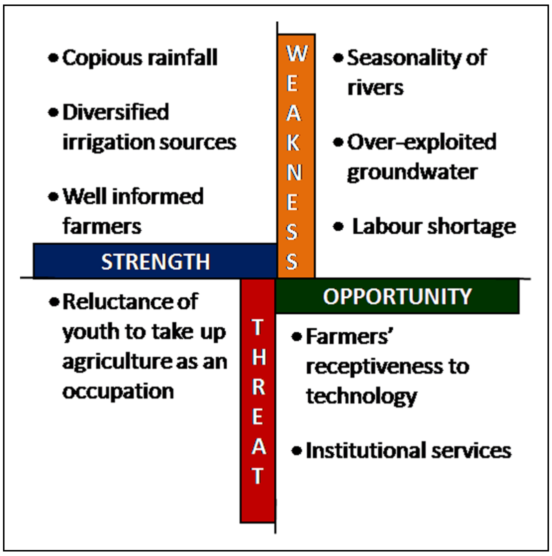

Figure 5. SWOT of Black gram-based Farming System.

water, *etc*.) from the gross income of INR 2,66,099, this farming system earned a net profit of INR 1,63,972/3 ha/annum.

A 3 ha BFS in Villupuram district that grows groundnut during *kharif* season; black gram, groundnut, and sesame during *rabi* season, and casuarina along with 3 cows incurred an expenditure of INR 88,734 and INR 52,308 per annum towards material inputs and labour respectively. All these farm operations generated 253 man-days which were partly fulfilled by 52% of family labour. Incidentally, the total fodder requirement amounting to INR 15,317 was purchased. After deducting the additional expenditure on interest and overheads from the gross income of INR 3,11,499, this farming system earned a net profit of INR 1,51,495/3 ha/annum.

A 2 ha PFS in Villupuram district that grows 3 paddy crops and sugarcane along with 3 cows incurred a relatively very high expenditure of INR 1,96,822 and INR 1,37,282 per annum towards material inputs and labour respectively. All these farm operations required 518 man-days which were partly fulfilled by 87% of family labour. As crop stover was sufficient to feed the cattle, this farming system did not incur fodder costs. After deducting the additional expenditure on interest and overheads from the gross income of INR 5,93,498, this farming system earned a net profit of INR 2,55,700/2 ha/annum.

A 3 ha IFS in Villupuram district that grows cotton and maize during *kharif* season; maize, cotton, black gram, groundnut, and sesame during *rabi* season; and tapioca and turmeric along with 5 cows and 10 goats while incurring a substantial expenditure of INR 1,85,870 towards material inputs, saved much on labour due to family labour contribution. Despite a whopping requirement of 477 man-days for the year-round farming operations, it incurred only INR 80,365 towards labour which was highly fulfilled by 85% of family labour. As crop stover was sufficient to feed the cattle in this system as well, there was no expenditure on fodder purchase. After deducting the additional expenditure incurred on interest and overheads from the gross income of INR 6,74,661, this farming system generated the highest net profit of INR 4,04,482/3 ha/annum.

Buoyed by high income and low explicit expenditure, IFS turned out to be the best performing farming system among the four representative farming systems of Villupuram and Virudhunagar districts.

Simulating potential interventions in the BFS

SWOT analysis. Apart from the copious rainfall, the major *strength* of BFS is the availability of diversified irrigation sources *viz.* rivers, dams, canals, tanks, ponds, and groundwater (Figure 5). Moreover, farmers are well informed of the developments in agriculture through personal contact with Extension Officials, media, *etc*. Nevertheless, the seasonality of rivers, over-exploited groundwater, and labour shortage are the major *weaknesses* of this farming system. Farmers are very receptive to technology and have good access to Institutional services *viz*. banks; input and output markets which offer a good *opportunity* to try out new enterprise combinations. At the same time, farmers are not willing their children to take over their profession, and hence, the lack of family labour combined with a shortage of hired labour pose an imminent *threat* to this farming system rendering a large proportion of the cultivable lands either fallow or diverted to non-agricultural purposes.

Proposed interventions. Considering the above SWOT status and FGDs with farmers and extension agencies, four different potential interventions were evaluated for BFS (Table 2).

Multi-bloom technology in black gram (MBBG). Under this method of cultivation, in addition to the recommended dose of fertilizers, 30 kg Nitrogen is applied in the form of Urea on the 45^{th} day after sowing which induces second fleshing. While the crop duration is extended by 20–25 days, the yield is more than doubled. As black gram is cultivated as a sole crop under irrigated conditions and a few progressive farmers are already practising this technology, other farmers in this farming system may also be sensitized to take up the technology for potentially higher returns. Hence, the traditional black gram cultivation practise was replaced with multi-bloom technology.

Increased kharif acreage (area). As water shortage renders the farmers to leave most of their land either fallow during *kharif* season or go for less remunerative casuarina, they may be encouraged to adopt efficient irrigation methods *viz.* sprinklers, rain guns, and underground pipelines to conserve the precious little water to utilize for the second season. Hence, the acreage under *kharif* groundnut was increased from 0.15 ha to 1 ha.

Livestock improvement (livestock). To reduce the expenditure incurred on the purchase of fodder, 0.1 ha of casuarina was proposed to be replaced with fodder sorghum. The existing cross breed cows are yielding around 6 litres of milk per day which is sold in the nearby

Table 2. Interventions simulated on BFS, PFS and DFS in IAT.

Intervention	Description
BFS	
• Existing	*Kharif*: 0.15 ha groundnut; *Rabi*: 1.2 ha black gram + 0.45 ha groundnut + 0.15 ha sesame; Perennial: 1.2 ha casuarina; Livestock: 3 low yielding cows.
• Technology	*Kharif*: 0.15 ha groundnut; *Rabi*: 1.2 ha multi-blooming black gram + 0.45 ha groundnut + 0.15 ha sesame; Perennial: 1.2 ha casuarina; Livestock: 3 low yielding cows.
• Infrastructure	*Kharif*: 1 ha groundnut; *Rabi*: 1.2 ha black gram + 0.45 ha groundnut + 0.15 ha sesame; Perennial: 1.2 ha casuarina; Livestock: 3 low yielding cows.
• Enterprise trade-off/ technology	*Kharif*: 0.15 ha groundnut; *Rabi*: 1.2 ha black gram + 0.45 ha groundnut + 0.15 ha sesame; Perennial: 1.1 ha casuarina; Livestock: 0.1 ha fodder sorghum + 3 high yielding cows + 5 goats.
• Combined	*Kharif*: 1 ha groundnut; *Rabi*: 1.2 ha multi-blooming black gram + 0.45 ha groundnut + 0.15 ha sesame; Perennial: 1.1 ha casuarina; Livestock: 0.1 ha fodder sorghum + 3 high yielding cows + 5 goats.
PFS	
• Existing	*Kharif*: 1 ha paddy; *Rabi*: 1 ha paddy; Summer: 1 ha paddy; Annual: 1 ha sugarcane; Livestock: 3 low yielding cows.
• Enterprise trade-off	*Kharif*: 1 ha maize; *Rabi*: 1 ha paddy; Summer: 1 ha groundnut; Annual: 1 ha sugarcane; Livestock: 3 low yielding cows.
• Enterprise trade-off	*Kharif*: 1 ha paddy; *Rabi*: 1 ha paddy; Summer: 1 ha paddy; Annual: 0.5 ha tapioca + 0.5 ha turmeric; Livestock: 3 low yielding cows.
• Technology	*Kharif*: 1 ha paddy; *Rabi*: 1 ha paddy; Summer: 1 ha paddy; Annual: 1 ha sugarcane; Livestock: 3 high yielding cows + 5 goats.
• Combined	*Kharif*: 1 ha maize; *Rabi*: 1 ha paddy; Summer: 1 ha groundnut; Annual: 0.5 ha tapioca + 0.5 ha turmeric; Livestock: 3 high yielding cows + 5 goats.
DFS	
• Existing	*Rabi*: 0.6 ha maize + 0.6 ha sorghum + (0.6 ha cotton + black gram) + 0.2 ha groundnut; Livestock: 4 low yielding cows + 10 goats.
• Enterprise trade-off	*Rabi*: 1.2 ha maize + (0.6 ha cotton + black gram) + 0.2 ha groundnut; Livestock: 4 low yielding cows + 10 goats.
• Infrastructure	*Rabi*: 0.6 ha maize with 50% reduced yield gap + 0.6 ha sorghum + (0.6 ha cotton with 50% reduced yield gap + black gram) + 0.2 ha groundnut with 50% reduced yield gap; Livestock: 4 low yielding cows + 10 goats.
• Technology	*Rabi*: 0.6 ha maize + 0.6 ha sorghum + (0.6 ha cotton + black gram) + 0.2 ha groundnut; Livestock: 0.2 ha fodder sorghum + 4 high yielding cows + 20 goats.
• Combined	*Rabi*: 1.2 ha maize with 50% reduced yield gap + (0.6 ha cotton with 50% reduced yield gap + black gram) + 0.2 ha groundnut with 50% reduced yield gap; Livestock: 0.2 ha fodder sorghum + 4 high yielding cows + 20 goats.

Cooperative Societies at the rate of INR 23 per litre. Hence, replacing the low-yielding cows with high-yielding cows which could yield around 10 litres/day is a good feasible option and was included in the simulation. Further, as per the farmers' preference, 5 goats were added as a supplementary enterprise.

All these interventions are being incentivized by the Government through various schemes and thus align with its priority.

Combination of interventions. Finally, all the three potential interventions were combined to evaluate their cumulative impact on the performance of BFS as a whole.

Impact of simulated interventions on BFS. When compared to the baseline farming system, adoption of multi-bloom technology in black gram increased the input cost by 5% and labour cost by 10% due to an additional 8% labour requirement which utilized only an additional 1% of available

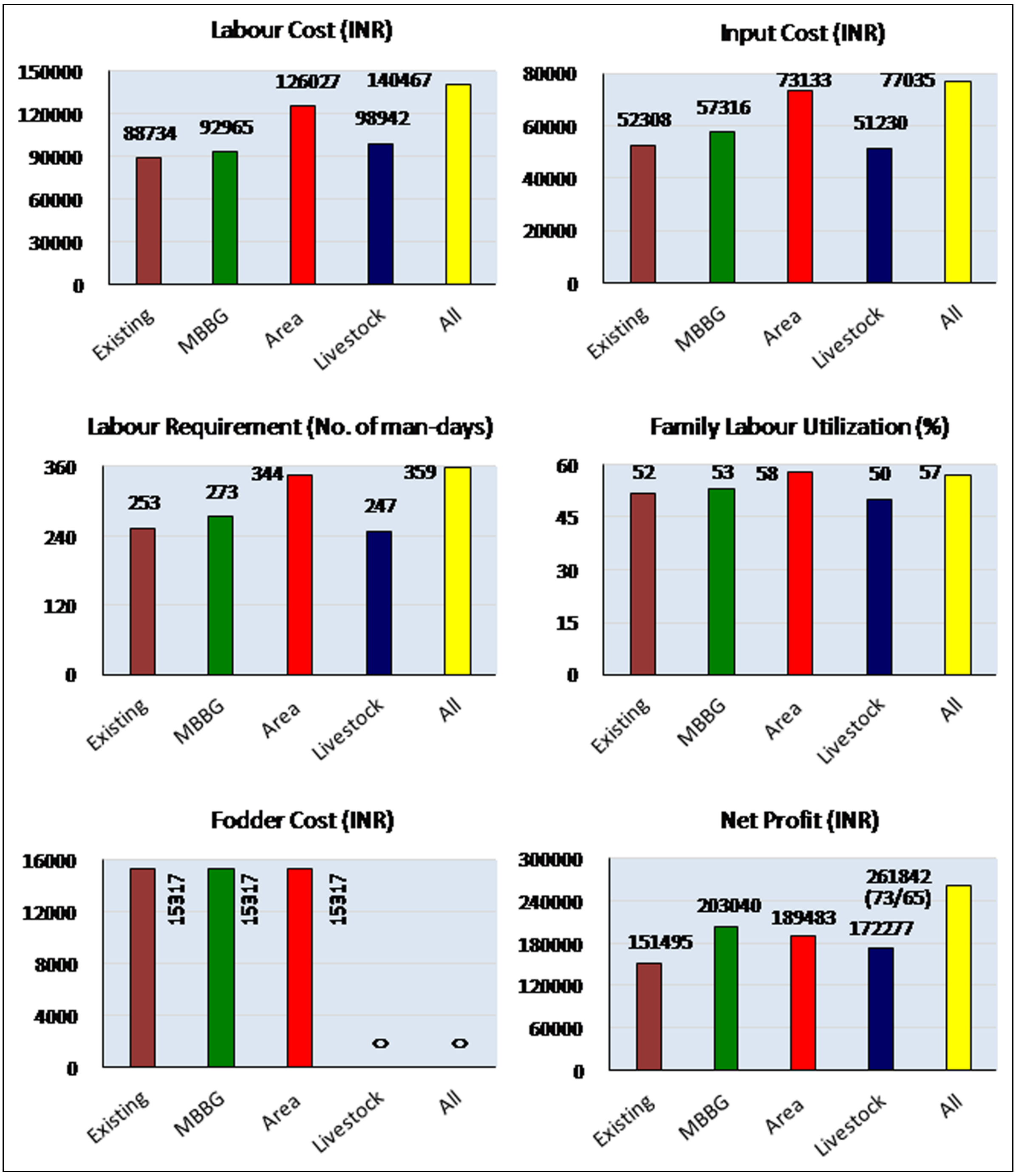

Figure 6. Impact of simulated interventions on Black gram-based Farming System: MBBG - multi-bloom technology in back gram, Area - increased kharif acreage, Livestock - livestock improvement, and 1 US Dollar (USD) = 63 Indian Rupee (INR).

family labour (Figure 6). As this technology does not influence fodder availability, there was no change in the expenditure on fodder. Notwithstanding the additional expenditure on input and labour, this technology increased the net profit of BFS by 34% from INR 1,51,495 to INR 2,03,040. On the other hand, increased acreage under *kharif* groundnut substantially increased the input cost by 42% and labour cost by 40% due to an additional 36% labour requirement which utilized only an additional 6% of available family labour. As this intervention too does not influence fodder availability, there was no change in the expenditure on fodder. Though an additional crop in *kharif* groundnut earned a sizeable gross income of INR 4,08,187 to the farm household, large expenditure towards input and labour left only 25% higher net profit for BFS from INR 1,51,495 to INR 1,89,483.

While the adoption of improved livestock management practices increased the material input cost by 12%, it reduced the labour cost by 2% due to a reduction in total labour and family labour requirement by the same proportion. Further, saving of expenditure on purchasing fodder due to fodder sorghum cultivation earned a gross income of INR 3,25,849 to the farm household. But, the advantage of livestock improvement was offset by the loss of revenue

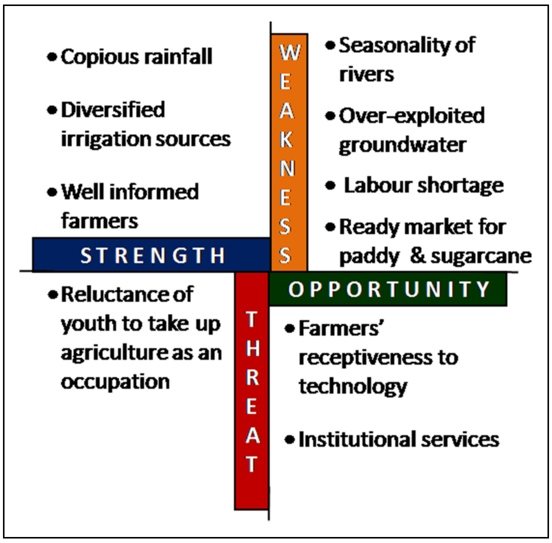

Figure 7. SWOT of Paddy-based Farming System.

from the foregone casuarina production, thus increasing the net profit of BFS by only 14% from INR 1,51,495 to INR 1,72,277. Altogether, the three interventions increased the input cost by 58% and labour cost by 47% due to 42% higher labour requirement and utilization of only an additional 5% of available family labour. But, the increased revenue and eventual savings from these interventions increased the net profit of BFS by 73% from INR 1,51,495 to INR 2,61,842 and helped to achieve 65% performance of IFS.

Simulating potential interventions in the PFS

SWOT analysis. Since PFS co-exists with BFS in Villupuram district, its SWOT is the same but the added *weakness* is the presence of many sugar factories in the vicinity that influence the farmers to take up water-intensive sugarcane cultivation (Figure 7). Moreover, paddy enjoys a sustained market demand and could be readily disposed-off to merchants either at the farm gate or at the nearby Agricultural Produce Market Committee.

Proposed interventions. With the above SWOT status and FGDs with farmers and extension agencies, four different potential interventions were evaluated for PFS emulating the IFS (Table 2).

Replacement of paddy with groundnut and maize (GN&M). The groundwater status across all blocks of Villupuram district has reached either the critical or over-exploited levels. Hence it is high time the water-intensive paddy and sugarcane are replaced with water-saving crops. Hence, the summer paddy and winter paddy were replaced with groundnut and maize respectively. Considering its less dependence on irrigation during *rabi* season, the monsoon paddy was retained.

Replacement of sugarcane with tapioca and turmeric (TT). Under this intervention, the remunerative but water-intensive sugarcane was replaced with equal acreage under water-efficient tapioca and turmeric.

Livestock improvement (livestock). As the crop stover takes care of fodder requirements in this farming system, only the low-yielding cows were replaced with high-yielding cows, and 5 goats were added as a supplementary enterprise.

Combination of interventions. Finally, all the above interventions were combined to evaluate their cumulative impact on the performance of PFS as a whole.

Impact of simulated interventions on PFS. When compared to the baseline farming system, replacing summer paddy with groundnut and winter paddy with maize increased the input cost by a marginal 2% and labour cost by 12% due to an additional 11% labour requirement which was fully hired leaving an additional 7% family labour idle (Figure 8). Overall, this crop replacement increased the net profit of PFS by 20% from INR 2,55,700 to INR 3,06,878. Even though replacing sugarcane with tapioca and turmeric decreased the input cost by a marginal 8% and labour cost by a substantial 51%, this intervention could increase the net profit of PFS by only 13% from INR 2,55,700 to INR 2,88,880.

While the adoption of improved livestock management practices increased the input cost by 6%, it showed no impact on labour utilization. By contributing a supplementary income to the farm household, this intervention increased the net profit of PFS by 6% from INR 2,55,700 to INR 2,70,548. Altogether, the three interventions had no impact on input cost but decreased the labour cost by 39% due to an 18% reduction in labour requirement. Equally buoyed by increased income and decreased expenditure, these interventions together increased the net profit of PFS by 43% from INR 2,55,700 to INR 3,64,666 and helped to achieve 90% performance of IFS.

Simulating potential interventions in the DFS

SWOT analysis. The major *strength* of DFS is the presence of rivers, reservoirs, tanks, and open wells (Figure 9). But their utility is marred by low and erratic rainfall, seasonality of rivers, rainfed nature of tanks, and un-utilizable groundwater. Amidst such constraints, farmers earnestly pursue farming by adopting various indigenous practices and coping strategies *viz*. manipulating sowing period, choosing between crops and varieties, intercropping, mixed cropping, bund cropping, relay cropping, and mixed farming. The presence of vast fallow lands and the farmers' knowledge of cultivating traditional nutri-cereals offer the best *opportunity* to promote such crops in this vast dryland tract by incentivizing and developing the irrigation infrastructure. If not acted upon quickly, it will be too late to utilize the potential of this farming system, as more and more Corporate are acquiring swathes of lands from hapless farmers who do not perceive cultivating their fallow lands in near future.

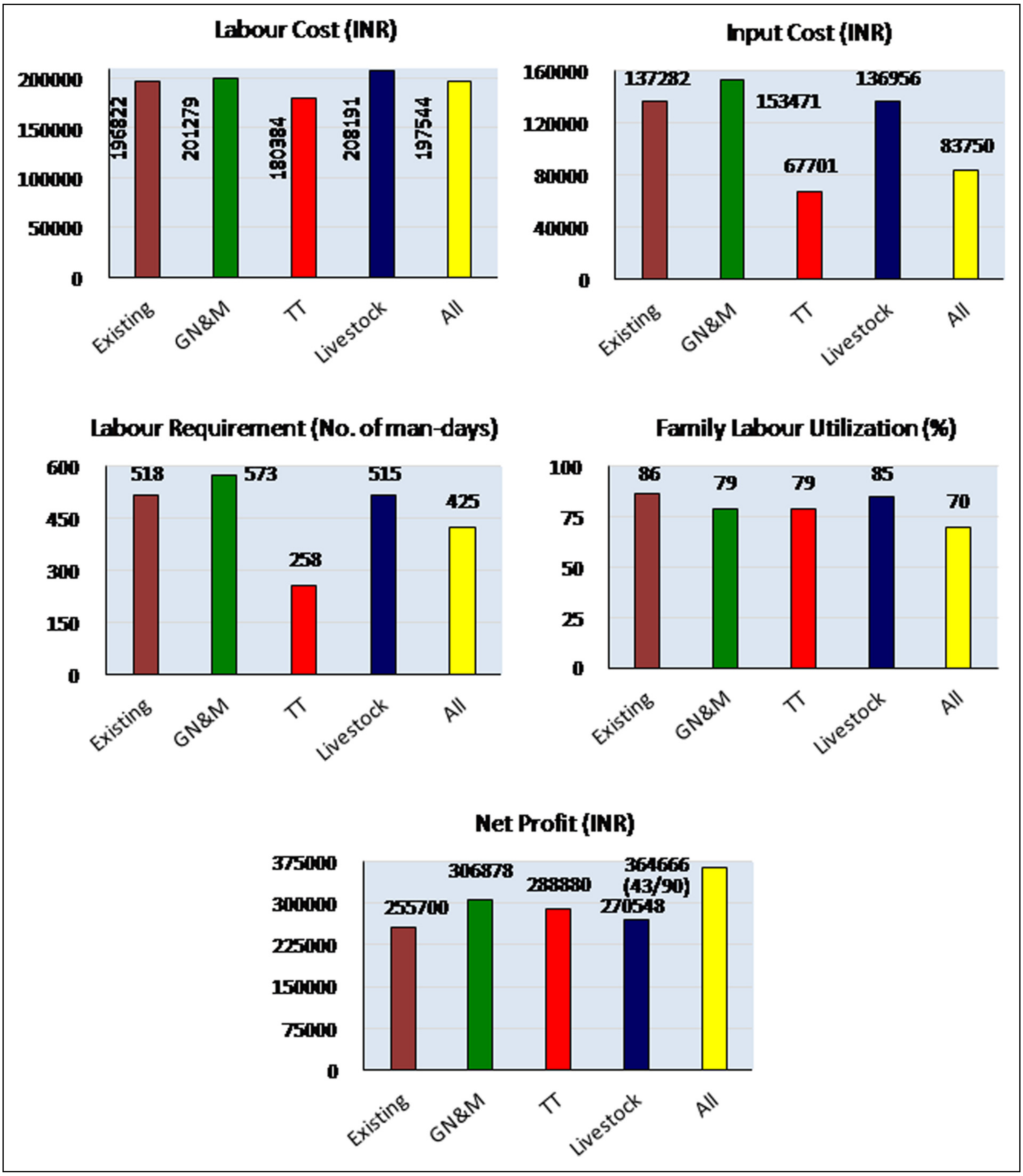

Figure 8. Impact of simulated interventions on Paddy-based Farming System: GN&M - replacing paddy with groundnut and maize, TT - replacing sugarcane with tapioca and turmeric, Livestock - livestock improvement, and 1 US Dollar (USD) = 63 Indian Rupee (INR).

Proposed interventions. With the above SWOT status and FGDs with farmers and extension agencies, four different potential interventions were evaluated for DFS (Table 2).

Replacement of low-value sorghum with high-value maize (value). Rainfall being low and erratic; and with no prospects of irrigation, farmers are compelled to cultivate low-yielding but sturdy millets *viz*. sorghum, barnyard grass, and pearl millet along with high yielding thus high value but resource-intensive maize as income insurance. Hence, the low-yielding sorghum was replaced with high-yielding maize.

Irrigation infrastructure improvement (water). Various public schemes promoting water harvesting and management *viz.* farm pond, community pond, and percolation pond are already in place in Virudhunagar district. Assuming that adoption of these practices provides supplemental irrigation to the dryland crops, the yield gap in cotton, maize, and groundnut was reduced by 50% as learned from a few case study farmers.

Livestock improvement (livestock). Similar to BFS, dryland farmers have to incur some expenditure towards

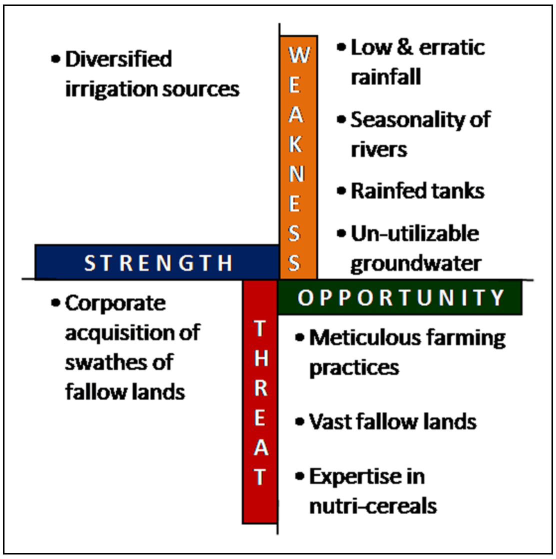

Figure 9. SWOT of Dryland Farming System..

the purchase of fodder. Hence, the cultivation of fodder sorghum in fallow lands was incorporated. Similarly, the existing low-yielding cows were replaced with high-yielding cows and the goat component was doubled as it offers huge potential for specialization in drylands with the help of various government schemes.

Combination of interventions. Finally, all the above interventions were combined to evaluate their cumulative impact on the performance of DFS as a whole.

Impact of simulated interventions on DFS. When compared to the baseline farming system, replacing low-yielding sorghum with high-yielding maize increased the input cost by 7% but decreased the labour cost by a marginal 2% (Figure 10). With an additional 6% fodder cost, this intervention increased the net profit of DFS by only 7% from INR 1,63,972 to INR 1,74,975. Similarly, bridging the yield gap in cotton, maize and groundnut increased the input cost by 4% but has not incurred additional expenditure on labour and fodder. Eventually, this intervention increased the net profit of DFS by 13% from INR 1,63,972 to INR 1,85,193. On the other hand, improved livestock management practices increased the input cost by 7%, not changed the labour cost but completely saved the fodder cost. With increased income from livestock and reduced expenditure on fodder, this intervention increased the net profit of DFS by a substantial 34% from INR 1,63,972 to INR 2,19,405. Altogether, the three interventions increased the input cost by 20%. But, the increased revenue from alternate crops and livestock management practices; and eventual savings in labour and fodder increased the net profit of DFS by 58% from INR 1,63,972 to INR 2,59,790 and helped to achieve 64% performance of IFS.

Discussion

From the interactions held with the officials of Agriculture Department, FGDs, and personal interviews with progressive farmers; and validating their perception with secondary data, this study identified four major farming systems prevalent in the study area *viz*. BFS, PFS, and IFS in Villupuram district and DFS in Virudhunagar district. Considering the prevailing farm holding size, cropping pattern, livestock management, socio-economic characteristics of the farm household, agricultural infrastructure, and institutional services, the identified farming systems were characterized to be representative of their respective region.

The IAT was parameterized for each of the representative farming systems with their respective climatic parameters, soil type, area under different enterprises, cropping pattern, quantity and quality of livestock, operation-wise cost of inputs, machinery and labour; overheads, availability of family labour, yield of crop, fodder, and livestock; their price, on-farm and off-farm income, *etc*. and the model was simulated for a 3-year rotation to evaluate their relative performance with respect to six indicators *viz.* input cost, labour cost, labour requirement, family labour utilization, fodder cost, and net profit.

While full utilization of land for round-the-year cultivation in IFS attracts a huge expenditure towards inputs *viz.* seed, fertilizer, pesticide, machinery, and irrigation, management by the resident farm household and maximum utilization of available family labour have considerably reduced the expenditure of an otherwise labour-intensive farming system. With a constant income flow from a continuous cropping pattern and a variety of livestock components, IFS sustainably earned the highest net profit. Though PFS too engages the land round the year and earns the next best net profit, the choice of water-intensive, labour-intensive, and input-intensive crops renders it unsustainable. Constrained by insufficient irrigation, high labour wages, and lack of family support BFS has to tread cautiously in engaging the land and choosing the enterprises. With moderate utilization of land, labour, and inputs, this farming system achieved a lower net profit. Similarly, DFS suffers from a lack of groundwater and irrigation infrastructure due to insufficient rainfall which left land and labour underutilized. Saved by water-efficient crops and supported by livestock, this farming system achieved a moderate net profit.

Unlike studies that strived to enhance the absolute performance of all the identified farming systems independently (Komarek et al., 2012), here the target was to enhance the performance of other farming systems to achieve the net profit equal to the best performing IFS sustainably (Mayberry et al., 2017). A typical smallholder operates a mixed crop-livestock farming system which integrates crop, forage, livestock, and labour; crops provide food for consumption and income, their residues to feed livestock; livestock, in turn, provide draft power to cultivate the land, manure to fertilize the soil, and milk for consumption and income; family labour is used on-farm and in non-farm roles (Herrero et al., 2014). As these activities are interlinked, any potential intervention may either increase or decrease production and consumption opportunities elsewhere with consequences for household welfare (Lisson et al., 2010).

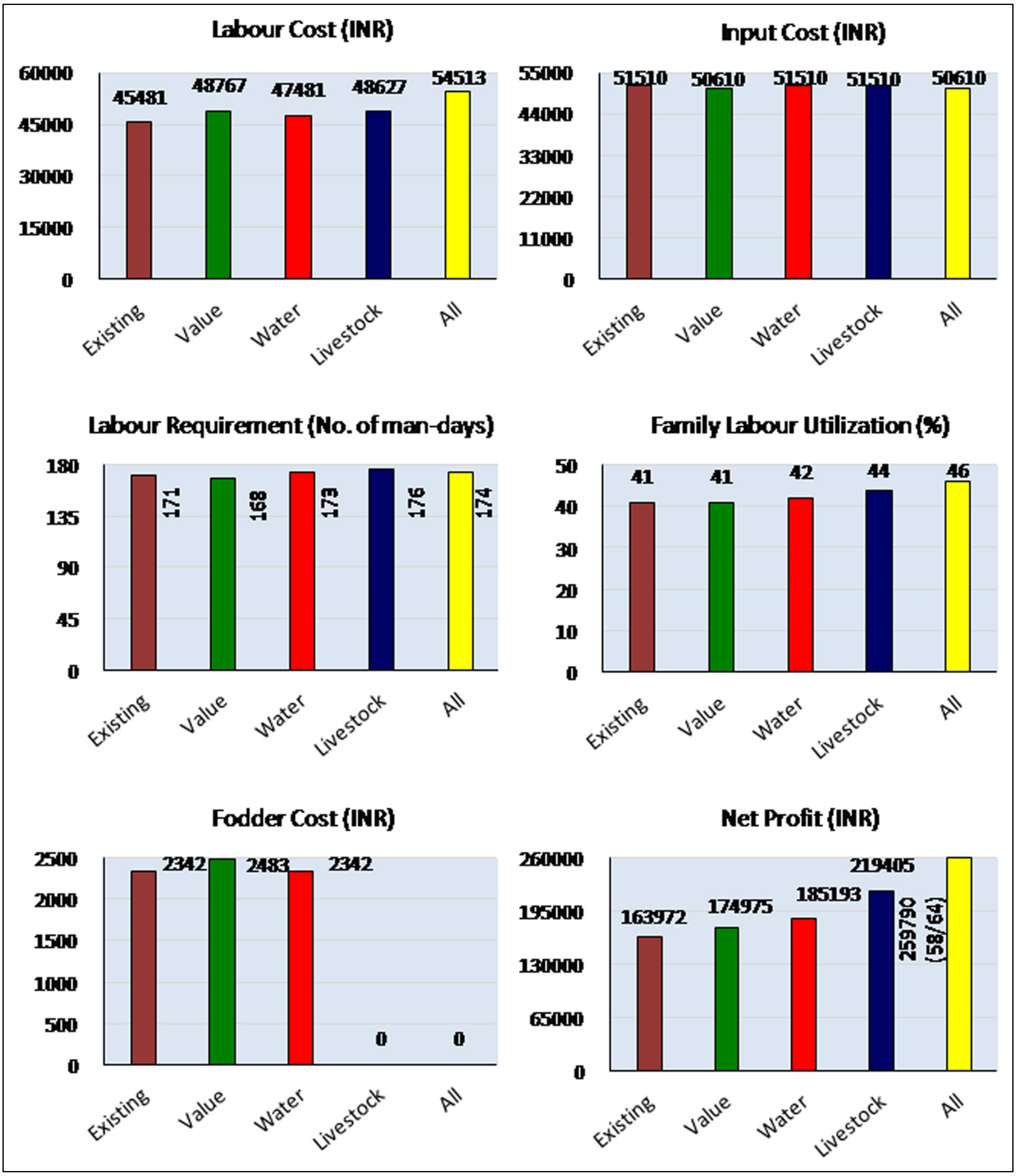

Figure 10. Impact of simulated interventions on Dryland Farming System: Value - replacing low value sorghum with high value maize, Water - irrigation infrastructure improvement, Livestock - livestock improvement, and 1 US Dollar (USD) = 63 Indian Rupee (INR).

Common interventions that are being simulated in a smallholder farming system are a) improved crop technologies *viz.* replacing low yielding varieties with high yielding ones (Louhichi and Paloma, 2014), row planting under irrigated conditions (Torkamani, 2005), enhanced fertilizer application (Paul et al., 2018; Rigolot et al., 2017), and using crop residues as mulching (Rigolot et al., 2017); b) crop acreage expansion (Louhichi and Paloma, 2014); c) introduction or expansion of fodder acreage (Komarek et al., 2012; Lisson et al., 2010; McDonald et al., 2019b; Monjardino et al., 2020; Paul et al., 2018); and d) improved livestock management *viz.* replacing low yielding livestock with high yielding ones (Paul et al., 2018; Shikuku et al., 2017), increasing the livestock numbers (Komarek et al., 2012; Lisson et al., 2010; McDonald et al., 2019b), and feed supplementation (Rigolot et al., 2017). The interventions are not necessarily those that optimize production or maximize income but are those that best fit into the existing farming system (McDonald et al., 2019b).

Technology in the form of row planting high yielding rice variety (Louhichi and Paloma, 2014), monogerm sugar beet seed and high yielding wheat variety (Torkamani, 2005) combined with enhanced fertilizer application (Paul et al., 2018) under irrigated conditions can lead to increased productivity, more profit and equitable benefit among adopters. But introducing such efficient technologies will not work in more specialized farming systems *viz*. paddy monocropping system due to rising marginal production costs and eventual replacement of existing cropping patterns impacting the livelihood of the farm household. Moreover, area expansion and productivity enhancement through high-yielding varieties are not possible without supportive irrigation infrastructure (Louhichi and Paloma, 2014) and labour availability (McDonald et al., 2019b).

On the other hand, introducing a forage crop into the existing cropping system will increase forage production (Lisson et al., 2010; Monjardino et al., 2020) but can harm grain crop production as it competes for available water. Similarly, replacing low yielding livestock with improved breeds can produce higher milk yields resulting in positive economic gains for farmers and improvement in food security (Henderson et al., 2016; Paul et al., 2018) but, increasing livestock numbers is not desirable in areas with scarce labour (Komarek et al., 2015).

In the present study, given their respective SWOT status, different interventions *viz*. multi-bloom technology in black gram, area expansion of *kharif* groundnut through efficient irrigation practices, introduction of fodder sorghum, and replacement of low yielding cows with high yielding cows within BFS; replacement of paddy with groundnut and maize, replacement of sugarcane with tapioca and turmeric; and replacement of low yielding cows with high yielding cows within PFS; and replacement of low-value sorghum with high-value maize, improving irrigation infrastructure to bridge the yield gap in cotton, maize, and groundnut; introduction of fodder sorghum, and replacement of low yielding cows with high yielding cows within DFS were simulated in the model to enhance their performance to those of the benchmark farming system indicators.

While multi-bloom technology in black gram increased the net profit of BFS by 34% without much stress on input and labour, area expansion under *kharif* groundnut through improved irrigation infrastructure incurred more expenditure on input and labour which considerably offset the gross income to realize only 25% higher net profit. Interventions in PFS incurred more expenditure in terms of both inputs and labour but cultivating maize and groundnut instead of paddy across two seasons significantly increased the net profit up to 20%. However, replacing sugarcane with tapioca and turmeric, despite providing huge savings on input and labour costs could not proportionally increase the net profit of the farming system. Given the supplementary role of livestock in BFS and PFS dominated by crop enterprises, improved livestock management practices have reasonably enhanced the net profit by 14% and 6% respectively. Incidentally, neither enterprise trade-off between sorghum and maize; nor increased yield of maize, cotton, and groundnut through improved irrigation infrastructure was enough to increase the performance of DFS to the desired level. But improved livestock management practices have substantially increased the net profit of this farming system by 34% with hardly any additional expenditure.

Strikingly, the irrigation endowed PFS has achieved 90% performance of IFS, the best farming system mainly through enterprise trade-off, whereas the water-starved BFS and DFS could achieve only around 65% performance of IFS through the combined implementation of technology, infrastructure, and enterprise trade-off, with a significant contribution from improved livestock management practices.

Conclusion and policy implication

Using the whole-farm modelling analysis, this study discerned the complexities involved in bringing out improvements to smallholder farming systems. While the ambitious intervention of expanding acreage and replacing low yielding traditional crops with high yielding ones will prove detrimental for a water-starved dryland farming system, even modest interventions *viz*. replacing a portion of casuarina with fodder sorghum or sugarcane with tapioca and turmeric that are aimed at enhancing the sustainability of respective farming systems will not earn the confidence of the participating farmers due to their adverse impact on the existing revenue. Similarly, an outright recommendation to expand the acreage under labour-intensive crops or to enlarge the herd size will not work in a labour-constrained farming system. Therefore, the agricultural policy must not only focus on potential interventions that are profitable but also consider what is acceptable to the farmers, taking into account the synergies and trade-offs between competing resources at the farm level (McDonald et al., 2019a) for which a better understanding of local conditions is required before designing and implementing interventions (Mayberry et al., 2017).

In this way, different potential interventions designed for other farming systems revealed that a "basket of options" rather than "few options" is appropriate to improve their performance *per se* and to catch up with that of the best performing IFS (Rigolot et al., 2017). Technology proved to be the best-fit strategy to bet upon as the added returns always outweigh added costs. Similarly, livestock improvement will be well received in dryland areas due to its reliability during adverse conditions. Though manipulating crop combinations may reduce gross returns as in the case of sugarcane, reduction in water, labour, and input usage increases the net profit and save the scarce resources. Water harvesting measures *viz.* farm ponds and Broad Bed and Furrow System provide supplemental irrigation and help in bridging the yield gap to a greater extent in dryland areas. Though the study envisaged more ambitious interventions to enhance the farmers' income, it restricted itself to modest options considering the SWOT of respective farming systems. Nevertheless, most of the evaluated interventions proved that the existing farming systems have huge scope for improvement.

Accordingly, innovative production technologies should be promoted in the well-informed BFS; farmers have to be incentivized to shift from water-intensive paddy and sugarcane to water-saving crops in groundwater depleted PFS; irrigation infrastructure should be developed in the water-starved DFS; and adapted high yielding livestock breeds, quality feeding, and fodder cultivation should be encouraged in all the farming systems to make them economically profitable and environmentally sustainable.

In furthering the cause of the study, the evaluated interventions should be tested on-farm at a larger scale to validate their simulated outcomes under diverse field conditions (Andrieu et al., 2012) and to provide an opportunity for the target-farm households to experience and evaluate the best-bet integrated strategies in the context of their farm and to demonstrate and communicate the benefits to other households (Lisson et al., 2010).

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Notes

1. https://des.tn.gov.in/
2. https://agritech.tnau.ac.in/govt_schemes_services/govt_serv_schems_nadp_dap.html
3. http://www.icar-crida.res.in/
4. https://agritech.tnau.ac.in/
5. https://research.csiro.au/livegaps/tools/integrated-analysis-tool-iat/

References

Andrieu N, Descheemaeker K, Sanou T, et al. (2015) Effects of technical interventions on flexibility of farming systems in Burkina Faso: Lessons for the design of innovations in West Africa. *Agricultural Systems* 136: 125–137. https://doi.org/10.1016/j.agsy.2015.02.010.

Andrieu N, Dugué P, Le Gal P, et al. (2012) Validating a whole farm modelling with stakeholders: Evidence from a West African case. *Journal of Agricultural Science* 4(9): 159–173. http://dx.doi.org/10.5539/jas.v4n9p159.

Bathgate A, Revell C and Kingwell R (2009) Identifying the value of pasture improvement using wholefarm modelling. *Agricultural Systems* 102: 48–57. https://doi.org/10.1016/j.agsy.2009.06.008.

Bhattacharyya R, Ghosh BN, Mishra PK, et al. (2015) Soil degradation in India: Challenges and potential solutions. *Sustainability* 7(4): 3528–3570. https://doi.org/10.3390/su7043528.

Chakrabarty M (2016) Climate change and food security in India. Issue No.157, Observer Research Foundation (ORF), New Delhi, India. https://www.orfonline.org/wp-content/uploads/2016/09/ORF_IssueBrief_1571.pdf.

Chand R (2017) Doubling farmers' income:Rationale, strategy, prospects and action plan. NITI Policy paper No.1/2017, National Institute for Transforming India, Government of India, New Delhi. https://www.niti.gov.in/writereaddata/files/document_publication/DOUBLING%20FARMERS%20INCOME.pdf.

Dev SM (2012) Small farmers in India: challenges and opportunities. Working Paper No.2012-014, Indira Gandhi Institute of Development Research, Mumbai, India. http://www.igidr.ac.in/pdf/publication/WP-2012-014.pdf.

GoI (2016) Agriculture census 2015–16. Agricultural Census Division, Department of Agriculture, Cooperation & Farmers Welfare, Ministry of Agriculture & Farmers Welfare, Government of India, New Delhi. http://agcensus.dacnet.nic.in. Last accessed on 03.01.2022

GoI (2019) Accidental deaths & suicides in India 2019. National Crime Records Bureau, Ministry of Home Affairs, Government of India. https://ncrb.gov.in/sites/default/files/ADSI_2019_FULL%20REPORT_updated.pdf.

Goswami R, Chatterjee S and Prasad B (2014) Farm types and their economic characterization in complex agro-ecosystems for informed extension intervention: Study from coastal West Bengal, India. *Agricultural and Food Economics* 2(5): 1-24. http://www.agrifoodecon.com/content/2/1/5.

GoT (2018) Statistical handbook of Tamil Nadu–2018. Department of Economics and Statistics, Government of Tamil Nadu. https://des.tn.gov.in/node/319.

GoT (2020) Agriculture department policy note demand No.5 – agriculture 2020–2021. Government of Tamilnadu. https://cms.tn.gov.in/sites/default/files/documents/agri_e_pn_2020_21.pdf.

Groot JCJ, Oomen GJM and Rossing WAH (2012) Multi-objective optimization and design of farming systems. *Agricultural Systems* 110: 63–77. https://doi.org/10.1016/j.agsy.2012.03.012.

Henderson B, Godde C, Medina-Hidalgo D, et al. (2016) Closing system-wide yield gaps to increase food production and mitigate GHGs among mixed crop–livestock smallholders in Sub-Saharan Africa. *Agricultural Systems* 143: 106–113. https://doi.org/10.1016/j.agsy.2015.12.006.

Herrero M, Thornton PK, Bernues A, et al. (2014) Exploring future changes in smallholder farming systems by linking socio-economic scenarios with regional and household models. *Global Environmental Change* 24(1): 165–182. https://doi.org/10.1016/j.gloenvcha.2013.12.008.

Köbrich C, Rehman T and Khan M (2003) Typification of farming systems for constructing representative farm models: Two illustrations of the application of multi-variate analyses in Chile and Pakistan. *Agricultural Systems* 76(1): 141–157. https://doi.org/10.1016/S0308-521X(02)00013-6.

Komarek AM, Bell LW, Whish JPW, et al. (2015) Whole-farm economic, risk and resource-use trade-offs associated with integrating forages into crop-livestock systems in western China. *Agricultural Systems* 133: 63–72. https://doi.org/10.1016/j.agsy.2014.10.008.

Komarek AM, McDonald CK, Bel LW, et al. (2012) Whole-farm effects of livestock intensification in smallholder systems in Gansu, China. *Agricultural Systems* 109: 16–24. https://doi.org/10.1016/j.agsy.2012.02.001.

Lisson S, MacLeod N, McDonald C, et al. (2010) A participatory, farming systems approach to improving Bali cattle production in the smallholder crop–livestock systems of Eastern Indonesia. *Agricultural Systems*103 (7): 486–497. https://doi.org/10.1016/j.agsy.2010.05.002.

Louhichi K and Paloma SGY (2014) Farm household model for agri-food policy analysis in developing countries: Application to smallholder farmers in Sierra Leone. *Food Policy* 45: 1–13. https://doi.org/10.1016/j.foodpol.2013.10.012.

Mayberry D, Ash A, Prestwidge D, et al. (2017) Yield gap analyses to estimate attainable bovine milk yields and evaluate options to increase production in Ethiopia and India. *Agricultural Systems* 155: 43–51. http://dx.doi.org/10.1016/j.agsy.2017.04.007.

McDonald C, Corfield J, MacLeod N, et al. (2019b) Enhancing the impact and sustainability of development strategies with smallholder farmers: Participatory engagement, whole farm modelling and farmer-led on-farm research. *International Journal of Agricultural Sustainability* 17(6): 445-457. https://doi.org/10.1080/14735903.2019. 1689063.

McDonald CK, MacLeod ND, Lisson S, et al. (2019a) The integrated analysis tool (IAT) – A model for the evaluation of crop-livestock and socio-economic interventions in smallholder farming systems. *Agricultural Systems* 176: 176-189. https://doi.org/10.1016/j.agsy.2019.102659.

Monjardino M, Philp JNM, Kuehne G, et al. (2020) Quantifying the value of adopting a post-rice legume crop to intensify mixed smallholder farms in Southeast Asia. *Agricultural Systems* 177: 1-12. https://doi.org/10.1016/j.agsy.2019.102690.

OECD/ICRIER (2018) *Agricultural Policies in India*. OECD Food and Agricultural Review. Paris: OECD publishing. https://www.oecd-ilibrary.org/sites/9789264302334-3-en/index.html?itemId=/content/component/9789264302334-3-en.

Paul BK, Frelat R, Birnholz C, et al. (2018) Agricultural intensification scenarios, household food availability and greenhouse gas emissions in Rwanda: Ex-ante impacts and trade-offs. *Agricultural Systems* 163: 16–26. https://doi.org/10.1016/j.agsy.2017.02.007.

Pingali P (2007) Agricultural growth and economic development: A view through the globalization lens. *Agricultural Economics* 37(s1): 1–12. https://doi.org/10.1111/j.1574-0862.2007.00231.x.

Planning Commission (2005) Tamil Nadu Development Report. Planning Commission, Government of India, New Delhi. Published by Academic Foundation, New Delhi. http://hdl.handle.net/123456789/536.

Rigolot C, de Voil P, Douxchamps S, et al. (2017) Interactions between intervention packages, climatic risk, climate change and food security in mixed crop-livestock systems in Burkina Faso. *Agricultural Systems* 151: 217–224. https://doi.org/10.1016/j.agsy.2015.12.017.

Sempore AW, Andrieu N, Nacro HB, et al. (2015) Relevancy and role of whole-farm models in supporting smallholder farmers in planning their agricultural season. *Environmental Modelling & Software* 68: 147–155. https://doi.org/10.1016/j.envsoft.2015.02.015.

Shikuku KM, Valdivia RO, Paul BK, et al. (2017) Prioritizing climate-smart livestock technologies in rural Tanzania: A minimum data approach. *Agricultural Systems* 151: 204–216. https://doi.org/10.1016/j.agsy.2016.06.004.

Torkamani J (2005) Using a whole-farm modelling approach to assess prospective technologies under uncertainty. *Agricultural Systems* 85: 138–154. https://doi.org/10.1016/j.agsy.2004.07.016.

Varadan RJ and Kumar P (2015) Mapping agricultural vulnerability of Tamil Nadu, India to climate change: A dynamic approach to take forward the vulnerability assessment methodology. *Climatic Change* 129(1-2): 159–181. https://doi.org/10.1007/s10584-015-1327-0.

World Bank (2007) World development report 2008: Agriculture for development. Washington, DC. http://hdl.handle.net/10986/5990.