

Article

Redesigning of Farming Systems Using a Multi-Criterion Assessment Tool for Sustainable Intensification and Nutritional Security in Northwestern India

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Citation: Prusty, A.K.; Natesan, R.; Panwar, A.S.; Jat, M.L.; Tetarwal, J.P.; López-Ridaura, S.; Adelhart Toorop, R.; Akker, J.v.d.; Kaur, J.; Ghasal, P.C.; et al. Redesigning of Farming Systems Using a Multi-Criterion Assessment Tool for Sustainable Intensification and Nutritional Security in Northwestern India. *Sustainability* **2022**, *14*, 3892. <https://doi.org/10.3390/su14073892>

Academic Editors: Anup Das, Subhash Babu, Jayanta Layek, Raghavendra Singh and Ramkrushna Gandhiji Idapuganti

Received: 27 January 2022

Accepted: 11 March 2022

Published: 25 March 2022

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Abstract: Sustaining agricultural systems dominated by small and vulnerable resource-poor farms that are subject to climatic aberrations is a major challenge for most Asian countries. In this context, the role of agriculture requires immediate attention in northwestern India where marginal farmers with less than a meagre 1 hectare of land represent about 67% of the population. Research based on prototype farms is being promoted in the redesign of current farming practices to help give these farmers sustainable livelihoods. We hypothesize that integrating innovative cropping systems into smallholder marginal farms could help to achieve these objectives. The study presented here describes a modelling approach for the ex-ante assessment of the current farming practices of marginal households in terms of economic, environmental, and nutritional indicators in comparison with those of experimental research farms in order to delineate an alternative scope of flexibility to optimize farming practices. We used the FarmDESIGN model to evaluate farmers' realities, with a focus on marginal farms (marginal poor farmers (MPFs)) and marginal diversified farmers (MDF) with the objective of enhancing profit, soil organic matter balance, and nutritional system yield in terms of dietary energy and reducing pesticide usage. Introducing prototype cropping systems in up to 33% of the farm area, combined with rearrangements of the existing crops, provided ample opportunity to improve farm performance. The improvements were greater when prototype cropping systems were added, and MPFs could benefit greatly from improvements in soil organic matter balance when considering the current negative organic matter balance of most farms. We conclude that the model-based approach of evaluating the potential of new cropping systems, along with the fine tuning of alternative combinations, will support the enhanced adaptability of innovative cropping practices, which will help to improve the livelihoods of marginal farmers.

Keywords: system analysis; whole-farm modeling; optimization; mixed farming system; sustainable agriculture

1. Introduction

Attaining food security for a growing population and alleviating poverty while sustaining agricultural systems that are dominated by small and vulnerable resource-poor farms subject to climatic aberrations is a major challenge for most Asian countries. Eighty-five percent of the Indian agrarian population are small and marginal farmers who have less than two hectares of land, of which a large portion (67%) are marginal farmers who have less than one hectare of land [1]. The livelihoods of these marginal farmers greatly depend on farm activities, which are often their only source of food security and income. The northwestern area has been the mainstay of food security, with the rice–wheat cropping system being the predominant cropping system [2]. However, the region today faces multiple challenges and constraints that threaten its sustainability, as is reflected in declining crop yields, natural resource degradation, the higher cost of inputs, and concerns regarding climate change, while the need of the ever-growing population for food and fodder increases [3,4]. This could be further aggravated with the deterioration of soil structure, declining underground water, erratic rainfall patterns, and fragmented landholdings, thereby hindering the realization of food production targets and threatening the food security of the country [5,6]. The research community faces the challenge of sustaining crop productivity, improving rural livelihoods, and securing environmental sustainability in the region, which requires a paradigm shift in the design of farming systems for the improvement of income and productivity while providing nutritional security in a sustainable manner.

Over the last decade, alternative cropping systems involving climate-smart agriculture practices have been promoted for the sustainable intensification of farming systems [4,7]. The diversification of cropping systems [5], as well as the development of location-specific integrated farming system (IFS) prototype farms, are other approaches previously used to cater to the needs of farmers [8,9]. The performance of these prototype farms has been encouraging [8]. However, the potential performance and impact of these practices evaluated in prototype research farms are unknown with regard to their on-farm performance, especially in smallholder farms, both in general and in India specifically. This restricts their development from on-station prototypes (a prototype developed at an experimental farm) to farm-scale adoption (adoption of these experimental prototypes on a large scale by farmers). Farming systems' approaches to agroecological engineering is of paramount importance in managing agricultural systems [10]. We hypothesize that the crop–animal–manure–soil interlinking for resource recycling will also contribute to soil health and cost reduction, whereas cropping systems with a diversity of crops, including fodder, have the potential to satisfy the food and fodder needs of households, thus improving food security and reducing the risks associated with monocropping.

A complete redesign of farms towards highly diversified systems may not be feasible, but the adoption of selected prototype elements may provide a realistic approach towards enhancing farming systems' sustainability. The pathway to change should match farmers' preferences and should account for the agricultural heterogeneity within the region, considering differences in income, land-holding, access to machinery, milk production, farm labor, household size, etc. [11,12]. Farms can be grouped into homogenous farm types and the socioeconomic condition of the farmers may be a key component in the adoption of new interventions and technologies at the farm scale [13–15]. Typology construction is a common method of dealing with farm diversity [16,17]. Multi-criterion assessment tools have been used to explore trade-offs and synergies among indicators of productivity, profitability, environmental impact, and nutritional security and to inform decision-making while mitigating risks [18,19]. Groot et al. [20,21] presented an integrative modeling approach embedded in a stakeholder participation setting.

In this paper, we characterize the diversity of existing farm types in northwestern India and assess the farm and household performance using multiple indicators. We compare smallholder farms with on-station prototypes and explore different options for improving the sustainability, nutritional security, and profitability of marginal farm households with promising cropping systems developed using prototypes.

The study focuses on exploring alternative options for marginal households by integrating the best combinations of promising cropping systems towards developing better farming strategies and development pathways at the regional and national level in order to encourage sustainable technology adoption at the farm scale.

2. Materials and Methods

2.1. Study Area

Northwestern India has a cereal-based cropping system with an emphasis on wheat. The climate sensitivity of agriculture in this part of India is very high. Decadal trends in the region's monthly and seasonal weather variables reveal a significant increasing trend of maximum temperature during the months of March and April. The average monthly minimum temperatures fluctuate from 6.7 to 7.5 °C in January (the coolest month) and from 23.4 to 25.2 °C in May (the hottest month). The average maximum temperatures range from 17.9 to 21.7 °C in January and 38.1 to 40.9 °C in May [22]. The average annual rainfall is 747 mm, and nearly 80% of the total rainfall comes from the southwest monsoon in June–September. August has the greatest rainfall (29.7% of total annual rainfall), followed by July (25.1%).

Livelihood strategies in the region predominantly revolve around crop–livestock systems and agricultural labor [23,24]. Wheat dominates the cropping pattern in winter and rice is important during the monsoon, with a significant role for sugarcane, with rice–wheat, sugarcane–ratoon–wheat, and sorghum–wheat being the predominant cropping systems followed in this region [25]. However, in recent years the system productivity of these systems has been decreasing for various reasons, including soil health deterioration due to cereal-based monocropping. Therefore, the exploration of alternative sustainable cropping options with diverse crops aimed at maintaining soil quality and improving system productivity may provide answers to address this issue.

Smallholder farmers have been deprived of the benefits of advancements in the field of agriculture, the major beneficiaries of which have been resourceful, well-endowed farmers [26]. Among livestock, buffalo is the most important dairy animal kept by farmers. Crossbred cows are also popular in the region. Farmers generally keep a mix of crossbred cows and buffaloes to fetch better prices from livestock rearing [24].

2.2. Survey and Typology Construction

A farm typology was constructed using survey data on 147 households to understand the diversity of farming systems in western Uttar Pradesh in northwestern India. Twenty different variables (Table 1) covering structural characteristics, livestock composition, crop diversity, cropping intensity, etc., were computed for 147 households and used for the development of a typology. A principal component analysis (PCA), followed by a hierarchical clustering analysis (HCA), was applied to define relatively homogeneous farm types. Many studies have used this approach to categorize farm types [12,14,16]. All analyses were executed in R (version 3.4.4) with the *ade4* package (version 1.7.13, available online: <http://pbil.univ-lyon1.fr/ADE-4/> (accessed on 26 October 2021)).

The decision regarding how many principal components (PCs) to keep was made based on three criteria: (i) according to Kaiser's criterion, all PCs exceeding an eigenvalue of 1.00 were initially retained and (ii) the scree plot test and minimum cumulative percentage of variance were chosen (56.3%). The final criterion, that of (iii) interpretability, was used to assess the conceptual meaning of the PCs in terms of the hypothesis under evaluation [27]. Hierarchical clustering was applied on the PCA results using the Ward method [28] and the dendrogram constructed served both as a visualization and partitioning tool. The optimal number of clusters was defined using the elbow method. After selecting the number of clusters to be retained, the suitable nomenclature was derived for farm types and the Kruskal–Wallis test was performed to identify significant differences in PCA variables and other variables.

Table 1. Variables used for the construction of household typology. The variables used in the principle component analysis (PCA) are indicated (X) [§].

Variable	Unit	PCA Variables
Sum of rented and owned land (totlandmanaged)	ha	X
Rented land	ha	
Land cultivated in kharif	%	
Land cultivated in rabi	%	
Land under sugarcane (landsugarcane)	%	X
Land under sorghum (landjawar)	%	X
Land under rice	%	
Land under wheat (landwheat)	%	X
Sorghum sold	%	
Wheat sold	%	
Harvested crops sold	%	
Sum of crops	Crop numberfarm ⁻¹ year ⁻¹	
Tropical livestock unit (TLU) [#] density	TLU ha ⁻¹	
Sum of tropical livestock units (TLUnumber)	number of TLUs	X
Animal products sold	%	
Total workforce involved in farming	number of people	
Adults living on farm	number of people	
Children living on farm	number of people	
Sum of adults and children living on farm (totalhhmembers)	number of people	X
Household (HH) members per hectare	HH members ha ⁻¹	

[#] Tropical livestock unit (TLU)—livestock numbers converted to a common unit [29]. [§] 6 uncorrelated variables were chosen for PCA analysis.

2.3. Prototype IFS Farms and Selection of Representative Farmers

Two prototype IFS farms, PT1 and PT2 (both 0.68 ha), with different cropping systems established in the ICAR-Indian Institute of Farming Systems Research (IIFSR) in Meerut, Uttar Pradesh, India situated in the study region under the All India Coordinated Research Project on IFS were taken as reference farms for the integration of their suitable components with marginal farms. The input/output relations of the cropping systems in these prototypes were quantified and used in the exploration of solution spaces for selected farm types [30]. One marginal farm (less than one hectare) of each type (near the center of the cluster in the typology) was considered. The selected representative farmer from each type was interviewed for in-depth characterization. An analysis was carried out of the current performance of the representative farmers, as well as solution spaces with or without the integration of the best-performing IFS prototype cropping systems.

2.4. Model-Based Analysis for the Assessment of Current Performance and Exploration

We used a static, exploratory, multi-criterion whole-farm assessment FarmDESIGN model that quantifies farm performance in terms of production, economic performance, and environmental performance based on annual resource flows [20]. The model employs an evolutionary algorithm, i.e., Pareto-based multi-objective differential evolution (P-MODE) [31,32]. The model was used to quantify the baseline performance of the prototype farms and the selected commercial farms and to explore alternative farm configurations with the P-MODE algorithm.

2.4.1. Model Parametrization

The FarmDESIGN tool [20] was employed to assess and compare the performance of the IFS prototypes (PT1 and PT2) and the two representative farmers (one farmer from each of the marginal farm types). The structural constituents of the IFS prototypes (PT1 and PT2) and representative real farm types (i.e., family size, land area, number of crops, TLU number, income contribution from crops and livestock) were compared using information

obtained through an in-depth survey of representative farms (for the real farms) and records (for the prototypes).

Primary data related to crops and cropping systems, livestock, yields, input usage, the destination of produce, labor hours, and the economics of cultivation were obtained through the records of the IFS prototypes and an in-depth survey of the farm for model input. Data regarding nutrient composition, energy value, and feed value were collected from the Indian Food Composition Tables issued by the National Institute of Nutrition [33] and Nutritive Value of Commonly Available Feeds and Fodders in India issued by the National Dairy Development Board [34]. When needed, this was supplemented with data from the USDA food composition table [35] and the Feedipedia animal feed resources information system [36]. The soil characteristics of the study site were obtained by analyses of soil samples from the IFS model site as well as the representative farmers' fields at the Soil Laboratory of ICAR-IIFSR, Meerut, while the weather parameters were obtained from the agromet observatory of ICAR-IIFSR.

For performance analysis, economic performance indicators such as operating profit per farm as well as per ha and gross margin from crops and animals and nutritional indicators such as nutritional system yield (NSY_E), i.e., food self-sufficiency in terms of dietary energy for no. of adults per ha, besides sustainability indicators such as pesticide use and soil organic matter balance, were considered.

2.4.2. Objectives and Constraints for Optimization and Optimization Runs

The following objectives were selected for the optimization and exploration of alternative farm configurations: (1) Maximize operating profit to improve economic performance ($\times 1000$ INR per ha. per year); (2) Maximize nutritional system dietary energy to enhance food self-sufficiency (adult persons per ha. per year); (3) Maximize soil organic matter balance (SOM) to improve soil fertility (kg OM per ha. per year); (4) Minimize pesticide use (active ingredient g per ha. per year).

P-MODE optimization was configured to generate 500 solutions representing alternative farm configurations after 4000 iterations of a Pareto-based evolutionary algorithm of differential evolution with crossover probability (CR) at 0.85 and amplitude of mutations $F = 0.15$ [20]. The minimum and maximum allowed values of decision and constraints for farm households for exploration of alternative solutions are given in Supplementary Table S1. The following constraints were used in the model: (1) Area of orchards, trees, boundary crops, fishponds, and kitchen gardens are fixed; (2) Livestock fixed at original values; (3) The feed balance for the animals are fixed on acceptable deviations of energy and protein; (4) Total water demand was fixed at the current water use of the farm.

The model was able to develop Pareto-optimal farm configurations for the stated objectives by exploring the association between farm components under given objectives and constraints. These configurations are re-arranged versions of the farm. These configurations generated by the model were visualized in a solution cloud. The purpose was to identify alternative solutions for the farm set-up that perform better with respect to the selected objectives as well as to assess the effect of these alternative cropping systems on the trade-offs appearing in the integrated assessment.

3. Results

3.1. Typology Construction

An analysis of the 147-household survey data with six uncorrelated variables was conducted with two PCs explaining $\sim 56\%$ of the variability (Supplementary Figure S1). Component 1 explained 30.3% of the variance and was correlated mainly with the structural component of the farms in terms of assets, i.e., total land managed by the household, TLU numbers, and total household members, while component 2 showed a correlation with the area allocation of crops and explained about 26% of the variance between farms (Supplementary Figures S2 and S3). These two components together explain 56.3% of the

variance. Hierarchical clustering analysis indicated three types consisting of 47, 60, and 40 farms, respectively (Table 2 and Supplementary Figure S4).

The mean characteristics of the different types of farm households obtained from a typology based on eight selected variables are presented in Table 2, which suggest two marginal farm types, i.e., marginal poor farmers (MPFs) and marginal diversified farmers (MDFs), who together represent 72.8% of farm households, while 27.2% of farmers belong to the medium well-endowed farmers (MWF).

Table 2. Means of variables for farm type of characterization.

Variable	Farm Type		
	Marginal Poor (MPF)	Marginal Diversified (MDF)	Medium Well-Endowed (MWF)
No. of Farm households nos. (%)	47 (31.98)	60 (40.81)	40 (27.21)
PCA Variables			
Total land managed (ha)	0.6	0.8	2.7
Cultivated land under sugarcane (%)	96.1	72.3	86.6
Cultivated land under sorghum (%)	3.6	22.7	9.4
Cultivated land under wheat (%)	48.9	44.5	23.5
Livestock number (TLU)	1.5	2.8	3.8
Number of household members	5.4	7.9	9.7
Other variables for farm characterisation			
Crop diversity	2.1	2.8	2.9
Number of adults members working in the field	1.96	2.93	4.38

3.2. Current Performance of IFS Prototype and Selected Marginal Farm Types

The marginal farm types were the focus of our analysis of the performance assessment. Marginal, poor farmers (Type MPF) cultivate the smallest amount of land and have smaller families than other farm types. This group of farmers allocates most land towards the cultivation of sugarcane as a cash crop. This group owns draft animals for cultivation and therefore a large percentage of cultivation cost is allocated to hiring field preparation instruments such as tractors. Meanwhile, marginal, diversified farmers (Type MDF) had larger households and were better off as compared to MPFs in terms of more cultivation area and more crop diversification.

Besides marginal local farms, two IFS prototype farms, i.e., PT1 and PT2 (both 0.68 ha), which were developed at the research station for marginal farmers, were also assessed. Taking into consideration the IFS prototype farm area and its similarity to marginal farm households, one MPF and one MDF farm type were considered for performance analysis and exploration. The representative MPF household had a cultivable area of 0.79 ha and five family members and cultivated sugarcane, oat, and wheat. Similarly, the selected farmer representing MDFs had 0.93 ha of cultivable land and six family members (Table 3). A detailed account of the structural composition of the two IFS prototypes (PT1 and PT2), along with two representative farm households, is described in Table 3. Current performance functional variables of all four farms in terms of operating profit, gross margin for crop and animal production, pesticide use, organic matter (OM) balance, nutritional system yield of dietary energy (NSYE) (no. of adult persons), and soil N loss using FarmDESIGN is presented in Table 3.

Table 3. Descriptive variables of two prototype farms (PT1 and PT2) and two representative marginal farm types identified in northwestern India.

Structural Variable	Farm Type			
	PT1	PT2	MPF (32%)	MDF (41%)
Family members (no.)	4	4	5	6
Arable land area (ha)	0.68	0.68	0.79	0.93
No. of animals	3 (buffalo)	2 (1 buffalo and 1 cow)	4 (1 buffalo, 1 cow, and 2 heifers)	2 (1 buffalo and 1 cow)
Crop varieties (no.)	12	21	3	5
Cow milk yield (litre year ⁻¹)	0	1497	3650	4745
Buffalo milk yield (litre year ⁻¹)	3500	2190	5110	3650
Income from crops (%)	43	65	45	63
Income from animals (%)	57	35	55	37
Arable Crops trees ⁻¹	Rice, Mustard, Oat, Chickpea, Wheat, Redgram, Maize, Sesbania, Banana, Kinnow, boundary plants	Rice, Wheat, Mustard, Chickpea, Green gram, Sesbania, Babycorn, Cowpea, Fodder *, Kinnow, Banana, Boundary plants	Sugarcane, Oat, Wheat	Banana, Sugarcane, Maize, Wheat + Sorghum
Performance indicators				
Operating profit (×1000 INR year ⁻¹)	270	234	221	449
Operating profit (×1000 INR ha ⁻¹ year ⁻¹)	397	347	280	483
Gross margin animals (×1000 INR year ⁻¹)	199	103	130	176
Gross margin crops (×1000 INR year ⁻¹)	79	192	107	298
Pesticide use (g AI ha ⁻¹ year ⁻¹)	372	1123	3418	3656
Pesticide use (g AI year ⁻¹)	253	758	2700	3400
OM balance (kg ha ⁻¹ year ⁻¹)	575	458	−121	−83
NSY _E (no. of adult person farm ⁻¹)	20.7	30.4	11.5	8.7
NSY _E (no. of adult person ha ⁻¹)	30.5	45	14.4	20.1
Water demand (m ³ year ⁻¹)	9020	8828	11,519	12,707
Water demand (m ³ ha ⁻¹)	13,265	13,079	14,406	13,664
Soil N loss (kg ha ⁻¹)	53	221.7	123	89

* Fodder includes sorghum, pearl millet, cowpea, maize, berseem, lucerne, oat, mustard, and ryegrass.

Current performance analysis revealed that the cropping pattern of local farms (both MPF and MDF) showed sugarcane–wheat dominance with fodder crops like oats and sorghum. The prototype IFS models had more diversification with cereals, pulses, and oilseeds besides fodder crops. Operating profits in IFS prototype farms were higher as compared to MPFs, while the MDFs with bananas provided higher return as compared to the prototype farms. In terms of pesticide use (g AI ha⁻¹ year⁻¹) and NSYE (yield ha⁻¹) the prototype farms performed better (Table 3).

3.3. Selection of Cropping Systems for Farm Scale Upscaling and Alternative Farm Exploration

To identify the suitable cropping systems of prototypes (PT1 and PT2) to be used in the exploration of alternative farm configurations, the performance per cropping pattern of both prototypes was assessed for the four indicators on a hectare basis using FarmDESIGN. Additionally the preference and acceptance of farmers were considered for the selection of cropping systems to be integrated to MPF and MDF farmers for solution space. A comparison of the desired objectives of cropping systems of both prototypes is given in Table 4. Four cropping systems were selected from prototypes for upscaling, i.e., including them in the explorations of the real farms assessed. To assess the impact of IFS cropping patterns, these were added as interventions in the model, and exploration (i.e., multi-

objective optimization) of relations among different objectives was carried out to obtain sets of possible alternative configurations for all farms with and without adding selected cropping patterns.

Table 4. Performance of selected cropping patterns under exploration.

Cropping Pattern of Reference Farms (PT1 and PT2) and Representative Marginal Farms (MPF and MDF)		Income ($\times 1000$ INR ha $^{-1}$) *	EOM (kg ha $^{-1}$)	NSY _E (No of Person ha $^{-1}$)	Pesticides (kg AI ha $^{-1}$)
PT1	CS1.1 Rice-Mustard	275.9	1711	41.8	0.69
	CS1.2 Sorghum (Green fodder)–Oat-Sesbania (GM)	154.4	3996	19.4	0
	CS1.3 Sorghum (Green fodder)–Chickpea-Sesbania (GM)	287.8	2224	11.2	1.13
	CS1.4 Maize + Redgram – Wheat + Mustard-Sesbania (GM)	230.2	1455	25.8	0
PT2	CS2.1 Basmati Rice (k) – Wheat + Mustard + sesbania (r)	130.3	2099	27.4	0.35
	CS2.2 Sesbania (k) – Chick Pea + Green Gram (r)	172.9	458	12.1	2.73
	CS2.3 Banana + Soybean (k) – Vegetable pea (r)	277.9	227	18.7	0
MPF	CS3.1 Sugarcane without intercrop	290.2	760	7.1	4.53
	CS3.2 Oat	113.5	469	7.1	0.73
	CS3.3 Wheat	196.6	407	29.1	3.01
MDF	CS4.1 Sugarcane with intercrop	247.2	1054	0	4.38
	CS4.2 Wheat	81.0	458	22.0	1.3
	CS4.3 Banana	930.3	508	53.8	5.0

* 1 USD = INR 74.38; EOM—effective organic matter, NSY_E—nutrition system yield in terms of dietary energy. Four cropping patterns (CS1.1, CS2.1, CS2.2, and CS2.3), were selected for integration into local farms for exploration.

3.4. Trade-Offs and Synergies (Exploration for Enhanced Farm Performance with Existing Cropping Systems and Alternative Farm Exploration Using Selected Cropping Patterns)

The current position of MPF and MDF farms belonging to marginal farm types and their solution spaces with respect to four objectives, i.e., to maximize operating profit, increase soil organic matter balance, increase dietary energy yield (nos. persons fed ha $^{-1}$), and minimize pesticide use, is presented in Figure 1. The result of the exploration provided relations between objectives in a cloud of solutions in two-dimensional space for both marginal farms (MPF and MDF). Both MPF and MDF farms had opportunities to improve performance for all objectives (Figure 1). The improvements that could be attained were larger when prototype cropping systems were added. The MPF farm could benefit greatly in terms of improvements in soil organic matter balance (Figure 1a,b,d).

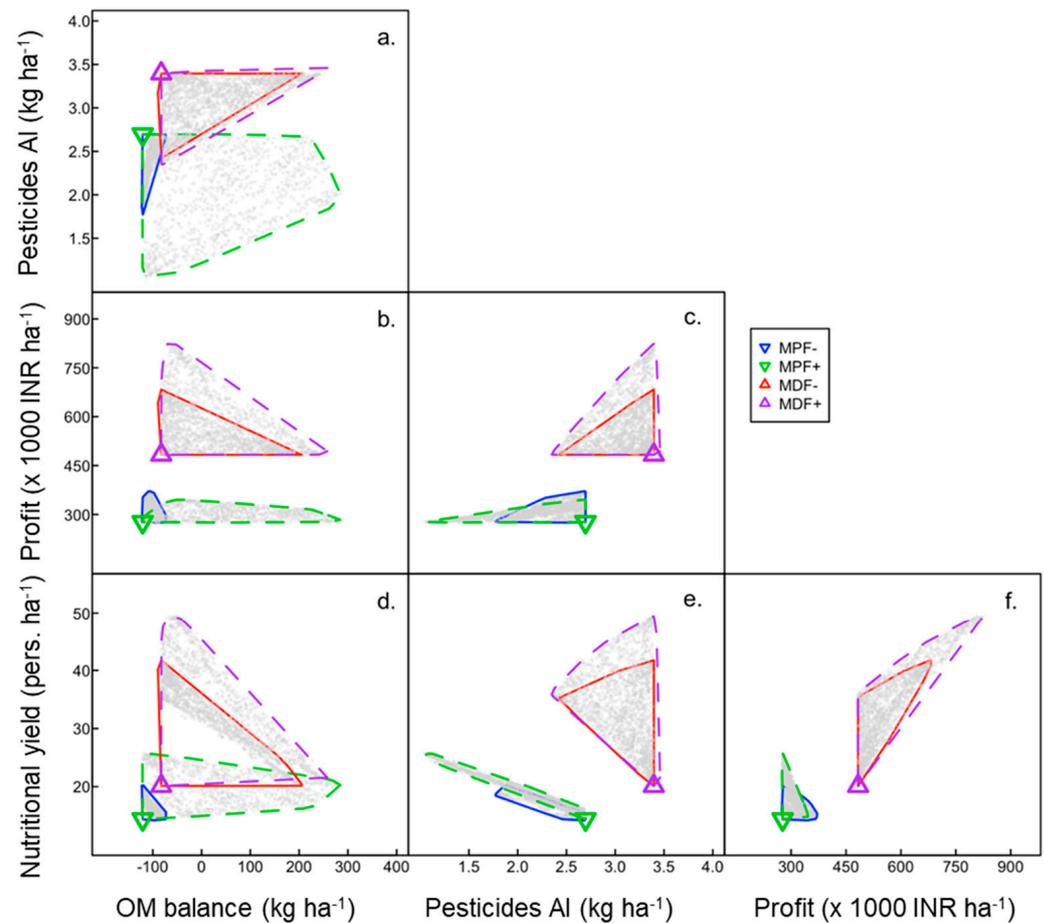


Figure 1. Solutions generated by multi-objective optimization with four objectives for MPFs and MDFs without (–) and with (+) prototype cropping systems. Relationship between the objectives: (a) pesticides AI vs. OM balance, (b) profit vs. OM balance, (c) profit vs. pesticides AI, (d) nutritional yield vs. OM balance, (e) nutritional yield vs. pesticides AI, (f) nutritional yield vs. profit. Each gray dot indicates an alternative farm configuration. The colored triangles with dashed lines depict a cloud of optimized alternative configurations for the respective farms with or without integration of selected cropping systems.

For the farm configuration generated for MPF with the highest OM cropping patterns, CS1 and CS2 would be incorporated for 5.5% and 27.0% of the cropping area, respectively (Figure 2a). For MDF, since considerable improvements in performance can already be made with existing cropping systems, only limited fractions of the prototype cropping systems were included, comprising between 12.0% and 33.0% of the cropping area in the solutions with the highest objective values—the “extremes” (Figure 2b).

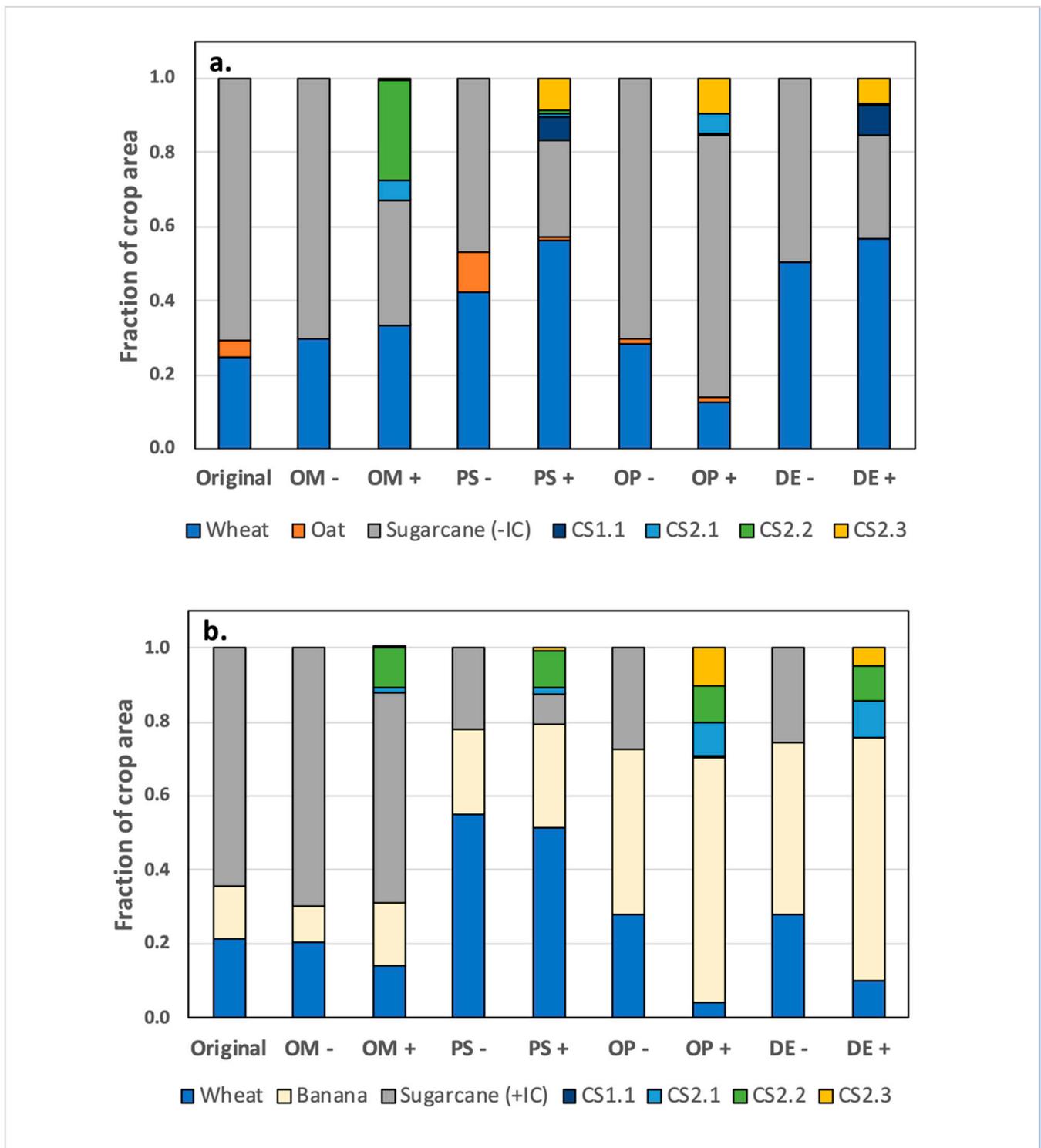


Figure 2. Crop area distribution for extreme solutions for the MPFs (a) and MDFs (b) with the highest organic matter balance (OM-, OM+), operating profit (OP-, OP+), and dietary energy yield (DE-, DE+) and lowest pesticide input (PS-, PS+), from exploration without (-) and with (+) intervention crops from prototypes—solutions that perform better than the original for all objectives. CS1.1: Rice–Mustard, CS2.1: Sorghum (Green fodder)–Oat–Sesbania (GM), CS2.2: Sorghum (Green fodder)–Chickpea–Sesbania (GM), CS2.3: Maize + Redgram – Wheat + Mustard–Sesbania (GM), IC, intercrop.

4. Discussion

The current method of developing innovations in cropping/farming systems is based almost entirely on conventional time and labor-intensive experimental results requiring model-based decision support to reduce trial and error learning through field experimentation [37]. The evaluation of a prototype's performance at the field scale through experimentation is difficult since the cost of experimentation limits the number of systems that can be tested in space and time [38]. Moreover, model-based analysis allows us to evaluate the new technologies or practices within the larger context of the whole farm and to determine the most suitable scale of deployment of the innovation in the farm. In this study, we combined information generated through surveys, experimentation, and modeling to (i) describe the diversity of farming systems in the region, (ii) assess their performance through multiple indicators and compared with prototype farms, and (iii) explore alternative options to improve their sustainability for the intensification for nutritional security. The information obtained was used for selecting potential cropping systems from prototype farms that have the potential for integration into commercial farms for designing possible alternative farm configurations through scenario exploration within given constraints. Similar strategies have been used, with on-farm interviews, participatory workshops, and bio-economic modeling to compare the performance of local farms with the prototype farm system and assess the potential role of the prototype farm system for farm development [39]. The whole farm model FarmDESIGN was used to generate alternative solutions with or without the integration of selected cropping systems from the prototype farms that resulted in increased economic efficiency while taking care of environmental health in terms of reduced pesticide application, in addition to addressing the nutritional concerns in terms of enhanced dietary energy yield. The application of optimization models plays an increasingly important role in the development of sustainable land management across diverse agroecological and socioeconomic conditions because field and farm experiments require large amounts of resources and may still not provide sufficient information in space and time to identify appropriate and effective management practices. The optimization approach for tackling complex systems provides a solution that helps to bridge the gap between theoretical farm designs and farmer realities [40–42].

The model-based results showed that there was limited scope for enhancing the economic performance while addressing environmental concerns in current farms. In both current farms, the organic matter (OM) balances were negative, requiring increased organic matter inputs towards long-term sustainability and maintaining soil health. Negative OM balances may be the result of management decisions made for other purposes, not necessarily in response to environmental concerns, which farmers consider secondary as compared to productivity or economic results [43]. When looking at the solution spaces, the potential for improvements in the various indicators for the MDFs was larger both with and without alternative cropping patterns as compared to MPFs. More diversified farms have the potential for higher and more stable yields, increased profitability, and reduced long-term risks [44]. There was not much difference between the solution spaces of MDFs with or without alternative crops, suggesting that current cropping systems have the potential to achieve the desired objectives with an adjusted farm configuration, even without adding alternative cropping patterns. Economic profitability and prevailing policies drive even the marginal farmers with less land towards the cultivation of sugarcane with or without intercrops. It is reasonable to expect that farmers will choose cropping systems that maximize their profit given the resources and opportunities available to them at present, especially given the better marketing opportunities for sugarcane in western Uttar Pradesh [45]. However, sugarcane is an input-intensive and management-responsive crop and therefore requires efficient input management and sustained enhancement of soil health, including soil organic carbon, which is pivotal to achieving sustained productivity. However, as farmers are typically regarded as risk-averse, strategies to reduce the uncertainties inherent in agricultural production by considering objectives such as OM balance (addressing production sustainability), less pesticide usage (environmental

sustainability) and meeting household demand (reduce market dependency) by adopting a land allocation-based approach may provide beneficial effects [46,47].

With the objectives employed in this study, only small proportions of prototype-derived cropping systems of up to 33% of the farm area were generated (Figure 2). We did not explore alternative farm configurations that would result in radical changes in the existing system, making them less practically feasible. Nevertheless, these small adjustments, combined with rearrangements of the existing crops, provide ample opportunity to improve farm performance. Studies suggest that the management alternatives can improve and stabilize farm productivity and thereby enhance farm income through the efficient use of on-farm resources while curtailing the negative impacts on environment [19,48]. This supports the adoptability of the new cropping systems and would allow farmers to experiment at a small scale to fine-tune the proposed crop combination to their farm context.

Our analysis revealed that to improve the environmental performance of MPF diversification by integrating cropping patterns involving green manure and legume crops, e.g., sesbania (kharif) – chick pea + green gram (rabi). The integration of green manuring and legume crops can help improve the sustainability of cropping systems by maintaining the carrying capacity of the cropping system and increasing the availability of nutrients in the surface soil [49,50]. Green gram fits into climate-smart agriculture strategies by providing resilience to climate risk [51,52]. An ex-ante evaluation of the impact of potentially valuable new technologies or alternative ways of managing production on various farm types has been reported by several authors [53–55]. In our study, for MPF farm types, optimal alternatives for income suggested a 49% increase, along with a reduction of 0.7% in soil OM balance without the inclusion of alternatives with change in land allocation only, while a 41% increase in income as well as a 57% improvement in soil OM balance could be achieved with the integration of alternative cropping systems. The exploration study revealed that there was little difference in optimal solutions for MDF farm types in the presence and absence of alternative cropping systems. This could be related to the fact that there is already variation in the cropping systems of farm types that perform better. Similar studies in the Indo-Gangetic plain reported that the integration of alternative cropping systems resulted in a 41% improvement in farm income, along with a 37% enhancement in soil OM balance for marginal farm types [56].

Can the same productivity and product quality be achieved on-farm as has been achieved on-station where the prototype cropping systems were developed and tested? In the early stages of adoption and adaptation, the farmer may lose some yield due to mistakes in the timing of the management operations and other aspects of crop cultivation. Moreover, there may be differences in the biophysical conditions such as soil fertility and water availability. Although the proposed areas of innovative cropping systems tested in prototypes were small, incorporating these on a farm would require more skills, knowledge, and technologies. Designing and implementing specific mechanisms such as communication platforms between researchers, farmers, and advisors may be useful to identify common problems and to discuss the value of alternative solutions [57,58]. These model-based explorations provide deeper insights into the complexities of mixed farming systems for tailor-made options based on multiple objectives and through different scenario analyses to target optimal solution space for smallholder farming systems. Furthermore, an analysis of the larger number of representative households per farm type along with a farmer participatory approach would open avenues for the targeted intervention of technologies and new management options. This would provide quality information for decision-makers on achieving improvements in farm performance using models as useful tools for analyzing the current and potential performance of farms to plan alternative combinations by taking into account short-term and long-term objectives.

5. Conclusions

In this study, we selected two farms representing farm types belonging to marginal poor farms (MPFs) and marginal diversified farms (MDFs) in northwestern India. We

observed heterogeneity in farm types with local farms being less diverse in terms of the number of crops they grew as compared to prototype research farms. The performance of the MPFs was lower in terms of operating profits as compared to MDFs and prototype farms. We conclude that the current cropping pattern in real farm types is more favorable towards maximizing profit as compared to other objectives. When environmental aspects of increasing the OM balance and reducing pesticide application rates are considered, prototype farm performance was better as compared to current farms, thus suggesting room for improved system performance in current farms via the re-allocation of current resources or the integration of alternative cropping patterns. The exploration of the window of opportunities for the four objectives using Pareto-based optimization demonstrated room to maneuver towards bridging the gap between local farms and prototype research farms. Explorative approaches using multi-criterion whole-farm assessment tools such as FarmDESIGN can help to provide a basis for tactical planning in the re-designing of farms towards sustainable intensification with an alternative window of opportunity to fulfil objectives such as soil health improvement, nutritional security of the farm family, and reduced chemical usage. The current approach of conducting a multi-criterion assessment of farming systems was able to handle the complexity of mixed crop–livestock farming systems when looking for new management options. We conclude that the integrative model-based approach of evaluating the potential of new cropping systems in complex systems and fine-tuning alternative combinations will support the enhanced adaptability of innovative cropping practices to provide a sustainable livelihood to marginal households.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su14073892/s1>, Figure S1: Scree plot of principal components with percentage explained variation, Figure S2: Variables projected on PC's, Figure S3: Colour code gives \cos^2 as means of representation (closer to 1 is more represented), Figure S4: Hierarchical cluster analysis dendrogram with three clusters, Table S1: Decision variables and constraints for the optimization of each representative of a marginal farm household typology.

Author Contributions: Conceptualization, A.K.P., R.A.T. and J.v.d.A.; methodology, J.C.J.G., S.L.-R. and L.B.-E.; investigation, A.K.P., P.C.G., R.A.T. and J.v.d.A.; writing—original draft, A.K.P.; writing—review and editing, J.C.J.G., S.L.-R., M.L.J., J.P.T., M.A.A., P.K., M.S. and J.K.; software, J.C.J.G.; funding acquisition, M.L.J., A.K.P. and R.N.; supervision, A.S.P. All authors have read and agreed to the published version of the manuscript.

Funding: This collaborative research was funded by the Indian Council of Agricultural Research (ICAR) and the CGIAR program on Climate Change, Agriculture, and Food Security (CCAFS) and Wheat Agri-Food Systems.

Institutional Review Board Statement: The survey was performed in accordance with their relevant guidelines and regulations and was approved by the technical program review committee of AICRP in IFS headed by the program coordinator and funding agency. We adhered to the Code of Ethics of the International Sociological Association (ISA) for the formulation and execution of the questionnaire. The questionnaire was also approved by the institutional committee at ICAR-IIFSR and pre-tested in the field before the final collection of data.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Acknowledgments: The authors acknowledge the technical support rendered by the Indian Council of Agricultural Research, All India Coordinated Research Project on Integrated Farming Systems (AICRP-IFS) and farmers involved in this work for sparing their valuable time, feedback, and participation in completing this work.

Conflicts of Interest: The authors declare no conflict of interest.

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