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# Farm typology analysis and technology assessment: An application in an arid region of South Asia

Shalander Kumar[a,b,*], Peter Craufurd[c], Amare Haileslassie[d], Thiagarajah Ramilan[e], Abhishek Rathore[a], Anthony Whitbread[a]

[a] International Crop Research Institute for Semi-Arid Tropics, Patancheru 502 324, India
[b] Indian Council of Agricultural Research, New Delhi, India
[c] International Maize and Wheat Improvement Center, Lalitpur, Kathmandu, Nepal
[d] International Water Management Institute, C/o ILRI Campus, Addis Ababa, Ethiopia
[e] Massey University, Palmerston North 4410, New Zealand

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ABSTRACT

The design and diffusion of context-specific technologies is centrally important in the multi-dimensional, complex farming systems in arid and semi-arid regions. This paper uses a mixed-method framework to characterize the complexity and heterogeneity of smallholder farming systems and identifies constraints to and opportunities for sustainable intensification. Specifically, the study: (i) characterized farm household typologies based on the diversity of livelihood assets; (ii) co-designed context- specific interventions through an iterative participatory process; and (iii) ex-ante evaluated such interventions to inform multiple stakeholders. We explored farming system diversity using data from 224 farm households in western Rajasthan, India. Employing multivariate statistical techniques and participatory validation, we identified 7 distinct farm household types. Participatory appraisal with multiple stakeholders revealed heterogeneity across farm household types. For instance, the interest of farmers in integrating perennial fruit trees even among the rainfed farm household types markedly varied: household type 1 preferred the multipurpose forestry tree, khejri which requires low labor inputs; household type 2 preferred market-oriented horticulture production; household type 3 did not opt for perennials but for small ruminants; and household type 4 (dominated by women) opted for small horticulture kitchen gardens. The study demonstrated the utility of a mixed-methods approach that addresses multi-dimensional heterogeneity to generate insights and assist in co-designing locally appropriate technologies across different farm types and agro-ecological regions to achieve sustainable intensification.

## 1. Introduction

Globally, the drylands which include the arid and semi-arid agro-ecological zones, occupy more than 6.09 billion ha and support the livelihoods of 35% of the world's population (van Ginkel et al., 2013). In India, dryland agriculture occupies 60% of the cultivated land. Low agricultural productivity, soil degradation, and other factors, both endogenic (e.g. land size, water, cultural, and demographic) and exogenic (e.g. weather, markets, and migration) are pervasive constraints in the dryland smallholder farming systems of India (van Ginkel et al., 2013). There is a need to address both agricultural productivity to meet the needs of the growing population and enable sustainable rural livelihoods in the dryland regions (van Ginkel et al., 2013). A wide variety of potential technological and policy solutions have been developed and tested by agricultural researchers, policy makers, and governments to tackle these issues. However, many such technologies and approaches with great potential have not been accepted by smallholder farmers. This could be attributed to the policy and development actors' inability to account for the heterogeneity in farming systems in terms of agro-ecological conditions, socio-economic environments, resource endowments, and farm management practices. Technological and policy interventions that have mostly focused on blanket solutions have been limited in delivering sustainable outcomes for dryland heterogeneous smallholder farming systems (Chang, 2012).

Often, agriculture and social sciences research for development are constrained by global scale evaluations that under-perceive and undervalue local complexities and diversity resulting in deterministic policy frameworks. Such inflexible policies for the development of

* Corresponding author at: ICRISAT, Building 212, ISD Program, Patancheru, 502 324, India.
*E-mail address:* k.shalander@cgiar.org (S. Kumar).

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agriculture and livelihoods in rural areas have proven ineffective (Chang, 2012). It is therefore vital to design technological and policy interventions that target diverse and spatially heterogeneous smallholder farming systems to address the pervasive constraints of the drylands. To date, few studies have attempted to tackle the complexity and heterogeneity of Indian dryland farming systems to derive effective strategies and policies (Goswami et al., 2014; Robert et al., 2017; Lopez-Riduara et al. 2018).

Indian smallholder farming systems are highly complex and heterogeneous in their characteristics: access to land, soil fertility, cropping systems, livestock assets, off-farm activities, labor, cash availability, socio-cultural traits, farm development trajectories, and livelihood strategies. Since it is impossible to develop unique recommendations for each household, farm diversity may be categorized to define recommendation domains (Kamanga et al., 2010; Tittonel et al., 2010). Recognizing variability within and among farms and across localities is the first step in designing interventions and policies to help poor farmers (Ruben and Pender, 2004; Mutoko et al., 2014). Farm household typologies can help summarize this variability and diversity among different farming systems (Kuhn and Offutt, 1999; Alvarez et al., 2018). Capturing this heterogeneity is an essential first step in the analysis of potential technological interventions and policy support. The selection of factors that define farm typology is governed by the purpose of the study (Köbrich et al., 2003). For example, farm typologies are used to study adoption of climate smart agriculture practices (Makate et al., 2018), food security (Lopez-Ridaura et al., 2018), resource use efficiency (Zingore et al., 2007; Tittonell et al., 2007), or overall classification of farm types (Goswami et al., 2014; Chatterjee et al., 2015; Andersen, 2010). In parallel, it is equally important to generate evidence of how context-specific understanding of constraints faced by the farmers in the adoption of technologies could shape future innovation strategies. A deeper understanding of such local scale constraints is needed to guide context-specific technological and policy interventions directed towards agricultural and rural development (Mwongera et al., 2017).

In this study, we attempt to capture the complexity and heterogeneity of Indian dryland farming systems and importantly, integrated this understanding in exploring pathways for sustainable intensification (SI) that increase resilience and improve farm incomes. To do this, we propose a characterization of household diversity based on a functional typology of key livelihood assets to identify and define farm systems[1] (not farming systems[2]) (Giller, 2013). Thus, for each group of relatively homogeneous farm systems, we can conceptualize and develop a "recommendation domain" (Giller, 2013). Using a participatory approach, an understanding is developed of the specific constraints faced by each of the identified farm types and the inventory of potential technologies for sustainable intensification of smallholder dryland farming systems. The objectives of this study were: (i) to identify farm household typologies that are representative of the heterogeneity of several factors in the dryland regions of India; (ii) to understand different farm system constraints and to analyze potential interventions through an ex-ante assessment of promising technologies that are identified by various stakeholders; and (iii) to develop a specific recommendation domain for each farm typology. This exercise of building farm household typologies and ex-ante assessment led to co-designing and piloting of context specific sustainable intensification interventions in western Rajasthan as part of the CGIAR research program on Dryland Systems. Thus, this study adds to the literature on operationalizing farm household typologies for better targeting SI interventions for smallholder dryland systems. We conclude by reflecting on how these typologies and their heterogeneity may be effectively used in designing an appropriate policy framework that supports innovation systems.

[1] **Farm system** refers to the conceptualization of an individual farm as a system, a set of inter-related, interacting components or sub-systems.

[2] **Farming system** refers to a single category within a broader typology, where the category groups together farms that are 'similarly structured'.

## 2. Methodology

### 2.1. Conceptual approach

We employed various system analytical methods, combining participatory research, farm system characterization using household typologies, and ex-ante economic assessment to identify intervention opportunities for sustainable intensification of dryland smallholder farm systems. A schematic representation of the conceptual framework is presented in Fig. 1. The approach begins with recognizing and describing farm household typologies. We integrated statistical and participatory methods for hypothesis-based typology construction using farm structural and functional data, firmly embedding local socio-economic, cultural, and biophysical contexts. We then identified specific constraints faced by each of the identified and validated farm household type and their consequences on agricultural production and livelihoods. This was followed by exploring and prioritizing farm-typology-wise agro-technological interventions together with farmers and other stakeholders. An ex-ante economic assessment of such prioritized interventions was performed. All this information was synthesized and analysed to explore system innovations that contribute towards sustainable intensification of smallholder dryland agriculture. A description of these steps follows.

### 2.2. The study areas: Location and biophysical setting

#### 2.2.1. Location

Rajasthan is India's largest state, covering about 10% of the country's total area. Its agro-ecology ranges from the very arid to semi-arid conditions with frequent droughts. Agriculture is therefore a very risky enterprise and highly vulnerable here. This study focused on eight villages in Jaisalmer, Barmer and Jodhpur districts in the arid eco-region of western Rajasthan (Fig. 2). These districts were selected by the CGIAR Research Program on Dryland Systems to serve as action sites that represent the arid and vulnerable eco-regions of South Asia (ICARDA, 2012). The selection was based on community and expert consultations, secondary data, and geospatial analysis, with the eight villages representing different farming systems in the arid eco-region (Table 1) (Dryland Systems, 2012).

#### 2.2.2. Biophysical setting

The study areas are characterized by limited seasonal precipitation with erratic distribution and high temperatures with large diurnal and seasonal variations (CAZRI, 2009). Although the villages are in an arid eco-region, mean annual rainfall shows an increasing trend from West to East, as does the inter-annual variation. Villages in Jaisalmer in the West are the driest with a mean annual rainfall of 150–170 mm (Table 1). Villages in Barmer and Jaisalmer are situated in an arid sandy plain while those in Jodhpur are in the alluvial plain of Luni Basin physiographic region (SRSAC, 2010).

Two soil types, Entisols and Aridiols, dominate the study sites. With a few exceptions, soils are sandy textured, shallow, and low in organic C and nutrients. Due to low rainfall, groundwater is being used extensively, with about 18% of the total cultivated area having access to irrigation. There is clear over-exploitation of groundwater. In Jodhpur, for example, groundwater is getting depleted at the rate of 0.17-0.89 m per year, while in Barmer and Jaisalmer it is estimated at less than 0.2 m per year (CGWB, 2008).

### 2.3. Farm household survey

Using a stratified random sampling technique, 256 farm households (30–35 from each village) were selected for the household survey. The

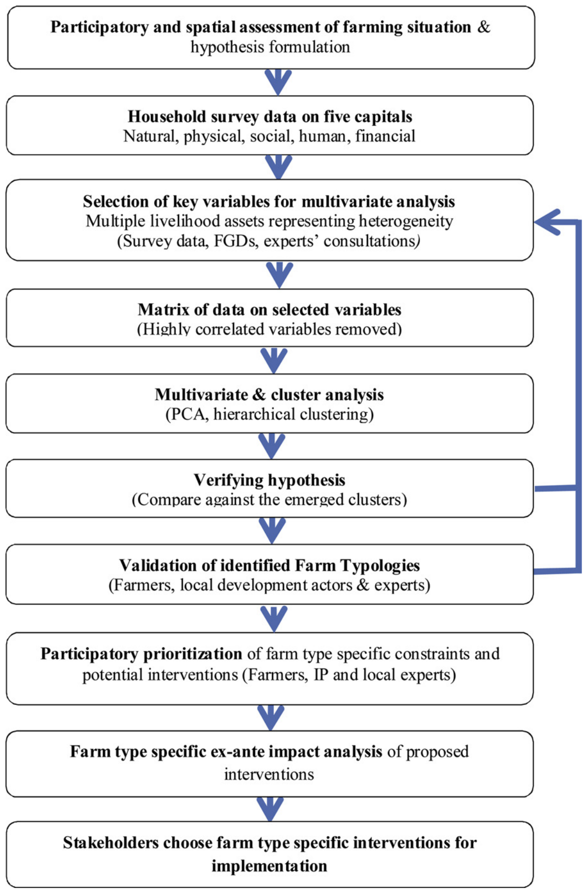


**Fig. 1.** Framework of farm household typology construction and prioritization of interventions.

districts, sub-districts (tehsil or taluk) and villages represented different strata in the sampling design. The selected households were surveyed during April and May 2013 with respect to data for the 2012/2013 whole production year. We adopted the livelihood assets approach (DFID, 1999) and used local expertise to identify indicators of the different assets which were then incorporated into the survey questionnaire and pre-tested. Survey questionnaires were designed to capture bio-physical, socio-economic, and managerial aspects of the farm household (Appendix 1). Socio-economic and farm information included livelihood assets, income sources, land use patterns, crop inputs, livestock systems, and market prices, etc. Participatory village appraisals and farmers' personal interviews were carried out to understand the level of heterogeneity in terms of major livelihood indicators including access to land, irrigation water, credit, training, and off-farm income sources. The household survey and interviews were preceded by focus group discussions (FGDs) involving farmers and key informant consultations in the study locations. While standardising the data, we removed the outliers and the households which are land-less and do not have complete information. The box-plot for key variables were used to identify the outliers. We also made sure that all categorical variables are recorded in numbers. We finally used data from 224 households for the farm typology analysis. This data was supplemented by case studies on the integration of fruit trees and agroforestry in the region, review of literature, and other published secondary sources. For example, the potential impact of intensification of Khejri *(Prosopis juliflora)* as an agroforestry intervention was assessed based on the long term study by Bhati and Faroda (1998), demonstrating the positive impact of Khejri on the yields of millets and legumes.

### 2.4. Farm household typology analysis

The participatory process initially led to the hypothesis that the magnitude of off-farm income, availability of family labor, type and size of livestock, access to water for irrigation, and integration of perennial trees are the key drivers of complexity in the dryland farming systems in western Rajasthan. In building the farm household typologies, we included both structural and functional traits of the farming systems. The structure relates to the purpose, degree of independence (for example, tenure), and size of the farm. The functional traits were captured through variables like education of the household head, level of input use, number of livelihood strategies, access to institutional finance, and level of crop diversity.

A multivariate approach was used to exploit the large number of recorded variables in the most efficient way. Statistical analysis was carried out using a Non-linear Principal Component Analysis (Non-linear PCA) and Cluster Analysis (CA) (Linting and Van der, 2012; Usai et al., 2006; Riveiro et al., 2013) using SAS PRINQUAL and CLUSTER procedures, respectively. Prior to the Non-linear PCA, the data's suitability for PCA was determined by Bartlett's test of sphericity and the Kaiser–Myer–Olkin (KMO) index to measure sampling adequacy.

Bartlett's test checks if the observed correlation matrix diverges significantly from the identity matrix. Further, the KMO criterion confirms that the factor analysis is appropriate for the sample. The value of KMO for the analysis was 0.67, which is regarded as acceptable (Field et al., 2012). PCA extracts linear combinations of the original variables whose weights correspond to the Eigen vectors of the correlation matrix. This approach allows a large part of the total variation to be concentrated in a smaller number of standardized uncorrelated variables. The variables were standardized before performing the PCA. Following the Non-linear PCA, farmers were grouped using Hierarchical Clustering Analysis using the principal component (PC) scores derived from PCA. Keeping with convention, a total of seven PCs with Eigen values more than or equal to one were used in cluster analysis to group the farm households into different types. Ward's method (minimum variance) was used because at each stage it joins the cluster pair whose merger minimizes the increase in total within-group error sum of squares, based on the Euclidean distance between centroids. It tends to produce homogeneous clusters and a symmetric hierarchy. The purpose of the cluster analysis was to minimize standard deviation within cluster means and maximize standard deviation of means between clusters.

The number of clusters was decided by Pseudo statistics and cubic clustering criterion (CCC) as well as a dendogram (Fig. 3), producing seven different clusters. Once the farm household typologies were constructed, farmers under each cluster were consulted to validate the grouping and to check for consistency across study locations. To test the significance of the difference in the magnitude of structural and functional variables across the farm household types, ANOVA was carried out.

### 2.5. Identifying and ranking constraints and potential interventions

Major constraints in the farming systems across the study locations were identified based on transect walks, household survey data, FGDs involving both survey and non-survey participants, consultations with the village development committee (VDC), and a multi-stakeholder innovation platform (IP). The VDC represents all groups of farmers including landless livestock keepers and women in each action village. The IP consisted of multiple stakeholders including agricultural researchers, local government departments, NGOs, industry, mid-level policy actors and farmers, and was initiated as part of CRP on Dryland Systems to strengthen the capacity of stakeholders to encourage diversification and enhance income generation by harnessing local and 'scientific' knowledge.

An inventory of agricultural production and livelihood related

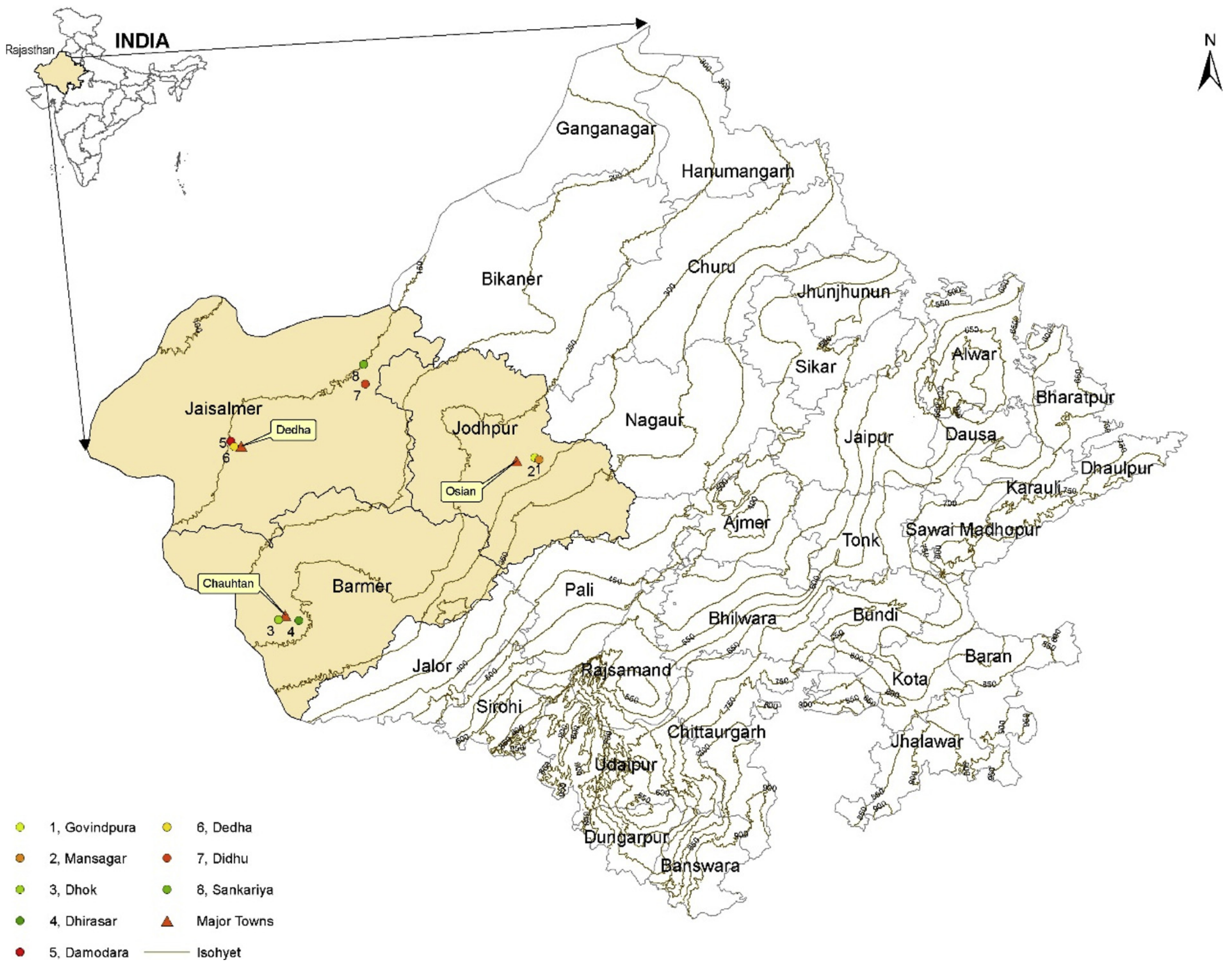


**Fig. 2.** Map of the study region with selected villages in Rajasthan.

**Table 1**
Key features of the study villages.
Source: Survey data (2013) and Taluk (sub-district) statistical records (2012).

| Key features | Unit | Study district, (Taluk) and village | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Jodhpur (Osien) | | Barmer (Chohtan) | | Jaisalmer (Jaisalmer) | | | |
| | | Mansagar | Govindpura | Dhok | Dihrasar | Dedha | Damodra | Sakariya | Didhu |
| Mean annual rainfall | Mm/ yr | 280 | 280 | 235 | 235 | 170 | 170 | 150 | 150 |
| Altitude | m | 233 | 241 | 163 | 128 | 221 | 162 | 106 | 157 |
| Total household | No. | 341 | 150 | 355 | 157 | 130 | 76 | 275 | 189 |
| Total area | Ha | 2443 | 1280 | 5063 | 1536 | 4041 | 4625 | 5093 | 13020 |
| Total population | No. | 2412 | 1143 | 2174 | 1037 | 823 | 516 | 1688 | 1216 |
| Irrigated area | Ha | 566 | 143 | NA | 0 | 0 | 0 | 917 | 810 |
| Average agricultural landholding | Ha/HH | 5.2 | 5.4 | 4.9 | 9.7 | 15.6 | 6.7 | 1.0 | 1.9 |
| Landholding per capita | Ha/ head | 0.72 | 0.71 | 0.79 | 1.45 | 2.45 | 1 | 0.12 | 0.29 |
| Area of rainfed farming | Ha | 1756 | 813 | 1739 | 1521 | 2030 | 516 | 215 | 359 |
| Livestock population | No. | 8625 | 3153 | 19633 | 20663 | 15758 | 10516 | 13881 | 8419 |
| LSI* | Ratio | 1.87 | 1.46 | 4.47 | 9.16 | 10.52 | 2.07 | 3.73 | 7.43 |

HH = household.
* LSI is livestock species index estimated as the ratio of small ruminants to large ruminants.

constraints was prepared and ranked on a scale of 1–10 (high to low) for each farm household (HH) type using a participatory pairwise ranking method actively involving farmers. Between 30 and 40 women and men (both survey and non-survey respondents) participated in such meetings conducted in each village. This ranking was done during the exercise of validating farm HH typologies. In a participatory prioritization process such as this, problems may arise due to conflicting interests of heterogeneous participants. Conducting this exercise for each individual homogeneous HH type helped us reduce such conflicting interests. Further, iterative addition and deletion of constraints from the list was part of the process. The final list of prioritized constraints for each of the farm HH types was then discussed in the IP meeting.

Following the discussion on constraints, IP meetings were conducted to identify and prioritize potential technological and institutional innovations to address constraints specific to the farm HH types.

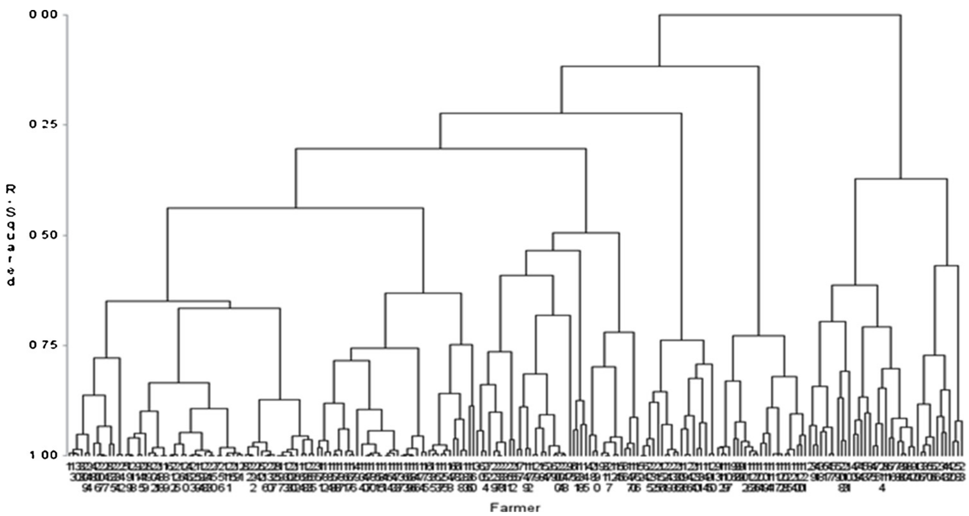


**Fig. 3.** Dendogram indicating the clustering of various farm households.

We used scientific (Bhati et al., 2017) and government reports, secondary data, and personal experiences to identify appropriate options for sustainable intensification of the existing farm systems. The IP served as a learning platform to integrate stakeholders perspective in identifying potential interventions to improve farming systems resilience and livelihoods. VDC and farmers from different HH types were next engaged in the prioritization of potential interventions. An iterative interaction between the IP and the VDC at every stage contributed to prioritization and implementation (on-farm assessment) of the most promising interventions across HH types. Finally, we developed a ranking matrix by which each of the identified intervention options was compared against other options pairwise. The participants were encouraged to come to a consensus on ranking feasible intervention options based on their local contexts.

### 2.6. Ex-ante assessment for priority options

This was followed by an ex-ante evaluation of some of the prioritized interventions, especially those that need long term investment, across each of the farm HH types, to judge their potential impact on enhancing farming systems resilience and increasing farm income. To enable comparisons in terms of the riskiness of different options, we estimated the coefficient of variation in yields of major crops across farm types using cross-section data as well as district level time series data for western Rajasthan from 2001 to 2010 (Fig. 4). We first calculated current and future returns from existing cropping systems for each of the farm HH types. Net returns per hectare for different crops were calculated from the baseline survey data, accounting for all costs including family labor but excluding the cost of land. The shadow price of family labor was considered the same as the market wage rate for labor, defined separately by gender. In-depth interviews of case study horticulture farmers, review of literature, field observations, and FGDs with extension staff were used to do an ex-ante impact assessment of the proposed alternate land use systems interventions.

The net present value (NPV) and internal rate of return (IRR) over a 20-year planning period were calculated for several system-level interventions following Gittinger (1982; 1984). Expert consultations and analyses of longer term rainfall records suggested that every third year is a drought year that reduces crop yields significantly. Based on those inputs, we assumed a 20–30% crop yield reduction every third year due to drought and accounted for this to calculate the NPV. The price of inputs and outputs to generate future streams of cost and returns were estimated based on the rate of increment in labor cost index (7.15%) and consumer price index (7.30%) over the past 10 years, with 2014 as the base year. The future stream of benefits need to be discounted using an appropriate discount rate to obtain their net present value (NPV). There is, however, little agreement among economists regarding what ought to be an appropriate discount rate. Referring to previous studies in the region (Alston et al., 1998; Kula, 2004; Alpuerto et al., 2009) and real interest rate, we initially applied a discount rate (r) of 8% in the

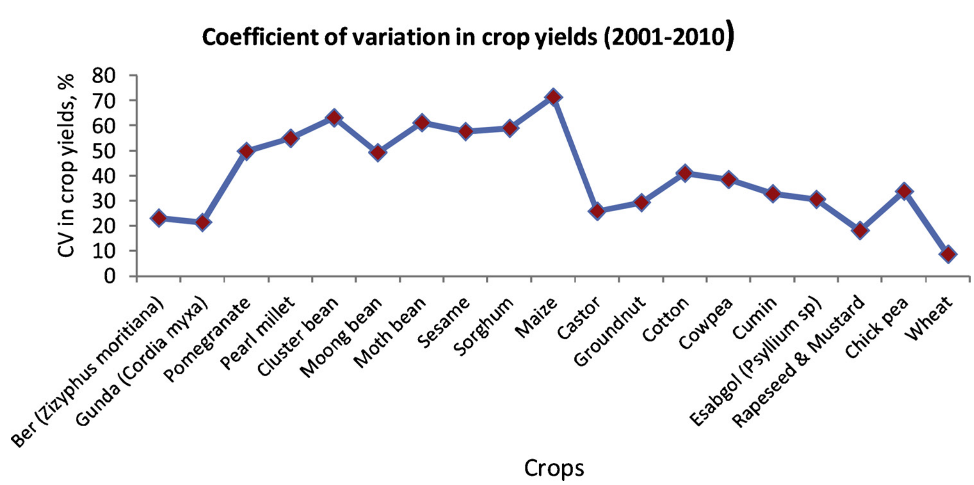


**Fig. 4.** Coefficient of variation in yields of major crops in western Rajasthan (2001–2010).

**Table 2**
PCA loadings for the first seven principal components (PCs) indicating the contribution of each variable through PCs for clustering the households.

| Variables | PC1 | PC2 | PC3 | PC4 | PC5 | PC6 | PC7 |
|---|---|---|---|---|---|---|---|
| Landholding size cultivated (ha) | 0.06 | 0.30 | 0.20 | 0.42 | 0.23 | 0.01 | 0.12 |
| Family labor available (no of days) | 0.14 | 0.14 | −0.37 | 0.18 | 0.35 | −0.28 | −0.41 |
| Standard livestock unit (SLU) | 0.14 | 0.53 | −0.02 | −0.01 | 0.04 | 0.14 | −0.01 |
| No. of crops grown per household | 0.15 | 0.45 | −0.03 | −0.31 | −0.35 | 0.05 | 0.09 |
| Income from livestock (%) | −0.32 | −0.26 | −0.11 | 0.14 | 0.22 | −0.04 | −0.24 |
| Income from off/non-farm earnings (%) | 0.32 | −0.18 | 0.33 | −0.14 | 0.00 | 0.23 | −0.28 |
| Manure applied (kg/ha) | 0.25 | −0.02 | −0.37 | 0.09 | −0.01 | −0.22 | 0.30 |
| Amount borrowed from bank/financial institutions (US$) | 0.37 | −0.09 | −0.06 | 0.15 | 0.11 | −0.06 | 0.20 |
| Total farm investment in past 5 years (US$) | 0.39 | −0.22 | 0.19 | −0.14 | 0.02 | 0.20 | −0.08 |
| Livestock diversity (no of species maintained) | 0.37 | −0.14 | −0.20 | 0.23 | 0.01 | 0.03 | 0.09 |
| Quantity of fertilizer used (kg/ha) | 0.15 | 0.37 | −0.15 | 0.01 | −0.06 | 0.06 | −0.49 |
| No. of livelihood strategies | −0.06 | 0.06 | −0.33 | 0.03 | 0.36 | 0.59 | 0.23 |
| Household head education (no of years in school) | 0.06 | 0.09 | 0.41 | −0.06 | 0.53 | 0.08 | −0.15 |
| Household head gender (Male = 1; Female = 0) | 0.12 | 0.09 | 0.23 | −0.16 | 0.20 | −0.63 | 0.13 |
| Access to canal (Yes = 1; No = 0) | −0.01 | 0.04 | −0.12 | −0.59 | 0.43 | −0.02 | 0.30 |
| Access to bore well (Yes = 1; No = 0) | 0.43 | −0.18 | 0.02 | 0.11 | −0.04 | 0.04 | 0.06 |
| Access to khadin (Yes = 1; No = 0) | −0.13 | 0.19 | 0.37 | 0.40 | −0.01 | 0.04 | 0.33 |
| Proportion Var | 0.24 | 0.13 | 0.08 | 0.08 | 0.07 | 0.07 | 0.06 |
| Cumulative Var | 0.24 | 0.37 | 0.45 | 0.53 | 0.60 | 0.66 | 0.72 |

present study. Though the actual market rate of interest in the region has been fairly stable for more than a decade, however, to understand the implications of variable interest rates, we undertook a sensitivity analysis using three discount rates: 6%, 8%, and 10%, especially evaluating the ex-ante impact of three major agro-horticulture systems. The farmers' yields of various annual crops like millets, legumes, etc is much lower than the achievable potential (CAZRI, 2009), in most cases less than a ton per hectare. To understand how the existing crops economics would compare with the alternative land use systems if the yield of existing crops is increased. Based on the experts' consultations we also generated scenarios of NPV from different crops over 20-year period at 15% increased yield and 30% increased yield levels.

## 3. Results

### 3.1. Farming system characterization

The arid ecosystems of western Rajasthan predominantly consist of small farms dependent on crop-tree-livestock components. The majority of farm families, especially in Jodhpur and Barmer, were located in hamlets (locally called *Dhani*) outside the villages. This arid region has a unique khadin system of cultivation (fed by runoff), an ancient land use system based on rainwater harvesting. It is mostly practiced in the 150–300 mm annual rainfall zone, wherein rocky catchments are used to collect runoff during the monsoon and allowed to percolate in the soil in low-lying farmland in order to raise crops on conserved moisture in the following winter season.

Low rainfall and frequent droughts result in highly variable and often low crop yields. Pearl millet is the most dominant crop together with cluster bean (*Cyamopsis tetragonoloba*), mung bean (*Vigna radiata*), moth bean (*Vigna aconitifolia*), and sesame (*Sesamum indicum*) grown under rainfed conditions. Wheat (*Triticum sativa*), cumin (*Cuminum cyminum*), and mustard (*Brassica juncea (*L.*)* are the major crops grown under irrigated conditions. Another major crop, chickpea (*Cicer arietinum*), is raised on conserved soil moisture or in some cases with limited irrigation in the rabi (postrainy) season. Practicing mixed and intercropping systems is a dominant risk management strategy for these farmers. Multipurpose trees are common throughout the region and effectively the landscape is a park land. Khejri (*Prosopis cineraria*), known as the lifeline of the Thar dessert, is a predominant multipurpose tree in this agro-ecological region. Other perennials, especially Ber (*Zyziphus mauritiana*), Gonda (*Cordia myxa*) and Amla *(Emblica officinalis)* under rainfed systems, and pomegranate (*Punica granatum*) and lemon (*Citrus limon*) under irrigated systems are also increasingly adopted in the existing farming systems. However, the role of trees in the farming systems has been decreasing due to land degradation and conversion of rangeland into cropland as well as the extensive use of tractors for ploughing (Jodha, 1986; Haileslassie et al., 2013). The density of Khejri as part of the park land system declined drastically from 27 trees/ha during the 1980s (Jodha, 2009) to 8.4 trees/ha in Jodhpur, 4.5 trees/ha in Barmer, and 2.4 trees/ha in Jaisalmer during 2014 in the study villages owing to multiple factors. Discussions with farmers in the study villages indicate that small ruminants [sheep (*Ovis aries*), goat (*Capra hircus*)] are the most important components of the traditional production system in Jaisalmer and Barmer. Along the West-East rainfall gradient, large ruminants [cattle (*Bos indicus* and *Bos taurus)*, buffalo (*Bubalus bubalis*)] are dominant in the mixed crop-livestock production system.

The major factor defining the structure of agricultural production systems along the West-East rainfall gradient is access to water/moisture. For example, with increasing extraction of groundwater, there has been a shift from traditional millets, legume crops, and livestock (cow and sheep) to commercial crops like cumin *(Cuminum cyminum (*L.*)* and Isabgol (*Plantago ovata*) and buffalo and goats. Traditionally, trees on common pasture lands and sacred groves were a major part of the system structure and a source of fodder for small ruminants. Owners of large flocks of small ruminants and cattle herds resort to intra/interstate migration in search of feed and water for animals, especially during severe droughts. Depending on the level of livelihood assets, off/non-farm income makes an important contribution to livelihoods. Understanding how these farm system dynamics in their structure and function relate to farm household types could help in better targeting long-term interventions.

#### 3.1.1. Farm household typology

A multivariate analysis of survey data from 224 farm households from the three arid districts of western Rajasthan resulted in the categorization of households into seven relatively homogeneous farm household (HH) types, reflecting differences in multiple livelihood assets. Initially, we carried out a Non-linear principal component analysis (PCA) with 32 livelihood asset variables. In an iterative process, highly correlated and less important variables were removed. Finally, the PCA contained 17 biophysical, socio-economic, and ecological variables. The first 7 principal components (PCs) with Eigen value of more than or equal to one which explained more than 72% of the variation were considered for cluster analysis (CA) (Table 2). Cluster analysis was done using the PCA scores of each observation for the selected seven components. The CA grouped the farmers into seven clusters. As part of this

**Table 3**
Structural and functional characteristics of households under different farm types.

| | Farm type 1 | Farm type 2 | Farm type 3 | Farm type 4 | Farm type 5 | Farm type 6 | Farm type 7 | P value |
|---|---|---|---|---|---|---|---|---|
| Landholding size cultivated (ha) | 3.91$^{a}$ (3.71) | 9.92$^{b}$ (17.42) | 10.82$^{b}$ (15.14) | 3.82$^{a}$ (3.28) | 3.56$^{a}$ (2.01) | 7.44$^{ab}$ (4.36) | 2.59$^{a}$ (1.52) | 0.0027 |
| Adult labor available (no.) | 4.06b$^{c}$ (1.99) | 4.63$^{cd}$ (2.19) | 3.16$^{a}$ (0.95) | 2.45$^{a}$ (0.78) | 3.40$^{ab}$ (1.67) | 5.14$^{d}$ (2.52) | 3.37$^{ab}$ (1.74) | < .0001 |
| Adult cattle units (no.) | 3.12$^{a}$ (2.06) | 10.86$^{c}$ (9.28) | 4.48$^{ab}$ (3.13) | 3.59$^{a}$ (3.97) | 5.14$^{ab}$ (3.21) | 6.83$^{b}$ (4.82) | 4.46$^{ab}$ (1.95) | < .0001 |
| No. of crops grown (per year per HH) | 2.68$^{ab}$ (1.21) | 2.68$^{ab}$ (1.15) | 2.23$^{a}$ (1.27) | 2.95$^{b}$ (1.22) | 2.26$^{ab}$ (0.81) | 5.67$^{d}$ (1.57) | 4.33$^{c}$ (1.56) | < .0001 |
| Income from livestock (% of total) | 12.32$^{a}$ (6.17) | 29.37$^{d}$ (12.64) | 12.83$^{a}$ (7.09) | 13.26$^{ab}$ (8.34) | 18.22$^{bc}$ (9.75) | 20.52$^{c}$ (10.8) | 17.92$^{abc}$ (7.22) | < .0001 |
| Income from off-farm earnings (% of total) | 60.15$^{c}$ (14.15) | 32.54$^{a}$ (16.49) | 48.58$^{b}$ (19.39) | 58.84$^{c}$ (17.51) | 44.35$^{b}$ (15.25) | 26.04$^{a}$ (19.61) | 26.83$^{a}$ (19.1) | < .0001 |
| Manure applied (kg/ha) | 69.26$^{a}$ (187.46) | 155.70$^{a}$ (449.2) | 60.29$^{a}$ (177.69) | 0.00$^{a}$ (0) | 121.83$^{a}$ (480.91) | 974.20$^{b}$ (1489.1) | 3715.26$^{c}$ (2760.36) | < .0001 |
| Institutional borrowings (INR) | 17,080.65$^{a}$ (36,607.6) | 39,268.29$^{a}$ (69,753.1) | 16,875.00$^{a}$ (38,508.8) | 32,789.47$^{a}$ (115,465.5) | 51,173.91$^{a}$ (88,968.1) | 280,370.3$^{b}$ (208,039.9) | 54,083.33$^{a}$ (78,347.1) | < .0001 |
| Total investment in past 5 years (INR) | 6279.03$^{ab}$ (19,058.4) | 19,768.29$^{abc}$ (78,091.8) | 38,079.38$^{abc}$ (118,512.1) | 4894.74$^{a}$ (11,663.78) | 62,769.57$^{ac}$ (147,215.2) | 366,648.4$^{e}$ (220,432.4) | 188,941.6$^{d}$ (175,581.2) | < .0001 |
| Livestock diversity (no. of species) | 1.81$^{a}$ (0.6) | 2.78$^{d}$ (0.94) | 1.60$^{a}$ (0.71) | 1.68$^{a}$ (0.89) | 1.91$^{ab}$ (0.42) | 2.30b$^{c}$ (0.61) | 2.58$^{cd}$ (0.67) | < .0001 |
| Quantity of fertilizer used (kg/ha) | 0.99$^{a}$ (6.14) | 0.53$^{a}$ (2.66) | 0.22$^{a}$ (1.42) | 1.64$^{a}$ (7.17) | 17.74$^{b}$ (12.95) | 48.34$^{c}$ (29.39) | 115.54$^{d}$ (65.24) | < .0001 |
| HH livelihood strategies (no.) | 3.11b$^{c}$ (0.83) | 3.15$^{bc}$ (0.79) | 2.93$^{ab}$ (0.86) | 3.47$^{c}$ (0.84) | 3.39$^{c}$ (0.94) | 3.15b$^{c}$ (0.82) | 2.50$^{a}$ (0.8) | 0.0272 |
| Female farmers as head of HH (%) | 0 | 7.32 | 0 | 100.0 | 0 | 0 | 0 | |
| Access to canal (% HH) | 0.00 | 2.44 | 0.00 | 0.00 | 100.00 | 3.70 | 0.00 | |
| Access to bore well (% HH) | 1.61 | 0.00 | 2.50 | 0.00 | 0.00 | 85.19 | 83.33 | |
| Access to khadin (% HH) | 0.00 | 17.07 | 87.50 | 21.05 | 0.00 | 0.00 | 0.00 | |
| Number of farmers | 62 | 41 | 40 | 19 | 23 | 27 | 12 | |

Note: Figures in parentheses are standard deviation of mean; multiple comparison test has been used to test the difference among means of the seven clusters. It indicates that 'a' is significantly different than 'b', 'c', 'd', 'e' and vice versa.

HH = Household; INR = Indian Rupee.

Khadin cultivation is a traditional land use system based on rainwater harvesting evolved and practiced in the 150–300 mm annual rainfall zone in western Rajasthan wherein rocky catchments are used to collect runoff during monsoon, which is allowed to percolate into the soil in low lying farmlands to raise crops on conserved moisture in the following post-rainy season.

characterization, we looked at both the farm structure and function. The structure emphasizes factors such as the purpose and size of the farm, while the function relates to productivity, income level, and production orientation (Table 3). The magnitude of most of the 17 livelihood assets was significantly different across the 7 farm household types, underlining the need for such clustering (Table 3). The resulting household types were named as:

1) Rainfed crops + off-farm income-based small landholders
2) Rainfed livestock-based large landholders
3) Rainfed crops + off-farm income-based large landholders
4) Rainfed crops + off-farm income-based small landholders – female-led household
5) Canal irrigated + off-farm income-based small landholders
6) Bore well irrigated + medium input diversified medium landholders
7) Bore well irrigated + high input diversified small landholders.

Rainfed farmers constituting 72% of the households were clustered into four farm HH types (1–4) with the remaining 28% of irrigated farm households were clustered into three HH types. The farm household typologies developed based on multiple livelihood assets are in contrast to the methodology commonly used in India using landholding size as the basis: marginal (up to 1.0 ha), small (1–2 ha), semi-medium (2–4 ha), upper-medium (4–10 ha), and large farmer ( > 10 ha) (Govt. of India, 2014).

We observed poor correlation between crop yields, net returns per standard livestock unit, and the size of the enterprise (correlation coefficient 0.0001 to 0.036). Values for the coefficient of variation (CV) of crop yields and net returns per standard livestock unit also indicate high variability across farm households during the same agricultural year, regardless of landholding size (Fig. 5). Such a result indicates that many livelihood assets and factors other than landholding size alone differentiate farm households in terms of their capacity to allocate and optimally utilize resources and adopt new interventions and technologies.

The PCA loadings presented in Table 2 indicate that the availability of family labor, access to a bore well for irrigation, percentage income from off/non-farm earnings, quantum of farm investment in the last 5 years, education of household head, level of fertilizer use, gender, livestock ownership, and crop diversity as well as landholding size were the key drivers for categorizing households into different farm HH types. Overall, multiple livelihood assets rather than landholding size alone played an important role in characterizing the households into different farm HH typologies.

The distribution of farm HH types is not uniform across the study locations (Table 4). Barmer district had households that predominantly belonged to either farm HH type 1, 2 or 4. Jodhpur had representation from all farm HH types, except type 5. Jaisalmer, a region with highly diverse resource endowments, also had all farm HH types, except the highly intensive HH type 7.

In the follow up typology validation exercise, about 90% of the participating farmers concurred with the classification of HH types and agreed that the farmers in each HH type had similar general characteristics and production strategies. The farmers also pointed out that though the landholding size varied within intra-household typologies (Fig. 6), overall a farm HH type managed their farms similarly and had comparable abilities and awareness about agricultural practices and technologies.

### 3.1.2. Farm structure and function

Farm HH types differed significantly in terms of their access to physical, natural, human, social and financial capital (Table 3). The difference in the magnitude of variables, like the share of off-farm income in household's total income, investment in the past 5 years, access to irrigation, levels of fertilizer use, livestock ownership, livestock diversity, and labor availability was highly significant across most of the

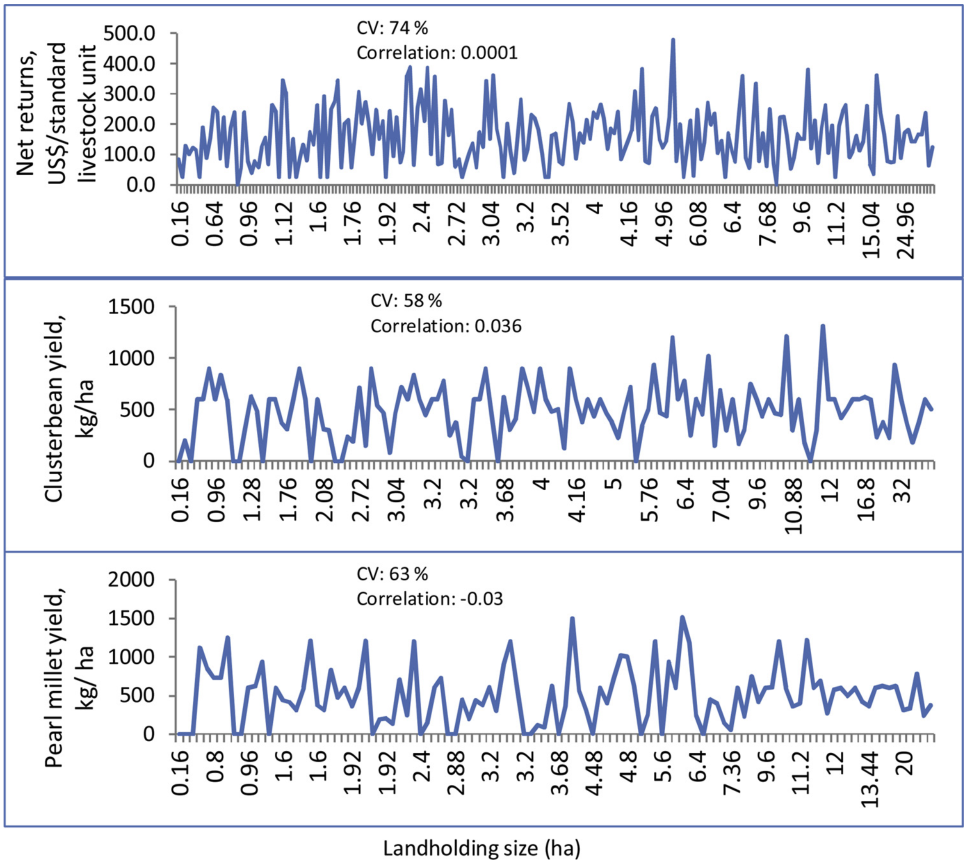


**Fig. 5.** Relationship between crop and livestock productivity and farm size, year 2012.

**Table 4**
Distribution of households across farm types and districts.

| District | Farm type 1 | Farm type 2 | Farm type 3 | Farm type 4 | Farm type 5 | Farm type 6 | Farm type 7 | Total |
|---|---|---|---|---|---|---|---|---|
| Jaisalmer | 23 | 18 | 38 | 10 | 23 | 15 | 0 | 127 |
| Barmer | 22 | 8 | 0 | 8 | 0 | 0 | 0 | 38 |
| Jodhpur | 17 | 15 | 2 | 1 | 0 | 12 | 12 | 59 |
| Total | 62 (27.6) | 41 (18.3) | 40 (17.9) | 19 (8.5) | 23 (10.3) | 27 (12.1) | 12 (5.3) | 224 (100) |

Note: Figures in parentheses are percent of total sample of farmers in a district/overall.

farm HH types (Table 3). The gender of the HH head, crop diversity, and livelihood strategies as well as yields of major crops were the other important cluster-defining variables. The results also align with the magnitude of PCA loadings, highlighting the key drivers of farm HH typology (Table 2). These structural and functional variables, including cultural preferences/family tradition, could influence the production orientation of different farm households (Pender et al., 2003). Therefore, understanding such heterogeneity will allow for better targeted interventions. How some of the important socio-economic and environmental indicators differed across the clustered farm HH types is discussed below.

*3.1.2.1. Socio-economic indicators*. *Landholding size*: Although landholding size was an important variable, its magnitude was not significantly different across HH types 1, 4, 5 and 7. HH types 2, 3, and 6 had similar landholding size that differed from other HH types (Table 3). However, the high standard deviation indicates high variability in landholding size within a HH type. Each farm HH type constituted households having different landholding sizes (Fig. 5) though their share varied across HH types.

*Labor supply*: Family labor availability also appeared to be one of the key drivers of heterogeneity and differed across farm HH types. HH type 4 (female headed) had the lowest availability of family labor, and the most diversified irrigated farm HH type 6 had the highest family labor available. Women and old male members of farm HH type 1 and 4 predominantly engaged in agricultural activities while the male members engaged in off-farm activities.

*Off/non-farm income*: The off/non-farm earnings were the major source of income for farm HH types 1–4 (all rainfed). Although HH types 2 and 3 had a larger farm size, HH type 2 showed a preference for livestock whereas HH type 3 engaged in off-farm work. The contribution of off/non-farm income was lowest in irrigated farm types 6 and 7. Farmers in the irrigated farm HH type 5, who faced greater uncertainty in canal water availability as compared to bore wells, also chose to diversify into off-farm activities as a major source of household income.

*Production orientation*: Crop production is a high risk enterprise in smallholder rainfed farm systems of western Rajasthan. This is evident from the high variability in crop yields and subsequently crop incomes across HH types (Table 5). This limits the farmers' ability to diversify investments into annual crops. As a risk management strategy, they tend to allocate resources to livestock production, agroforestry, and off-farm activities. Among the irrigated HH types 5–7, variables like land: labor ratio, level of certainty of access to irrigation water, access to credit, land size, education level, and access to extension services as well as crop and livestock productivity levels influenced production orientation (Table 3). Access to bore wells for irrigation was more reliable in farm HH type 6 and 7 than the canal water in HH type 5. Hence, farmers with access to bore wells could plan crop diversification and input use with more certainty compared to households with access to canal irrigation. However, the bore well owning households were further clustered into two farm HH types 6 and 7, mainly because of the

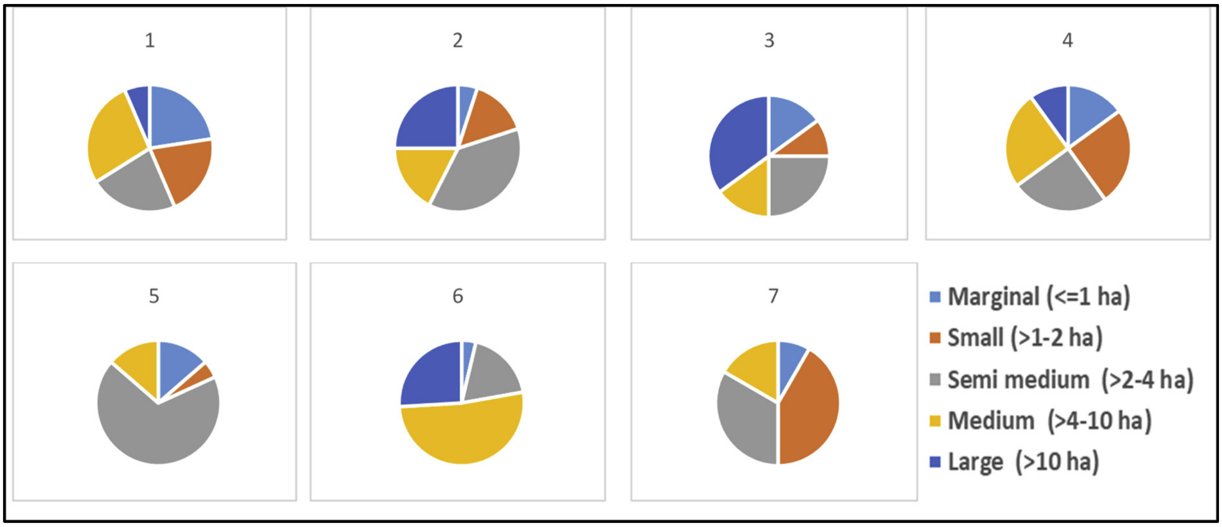


**Fig. 6.** Distribution of the study farm households under different land holding size across the farm HH types.

difference in the magnitude of variables like labor availability, land size, and farmer awareness level and risk taking ability, which were reflected in the level of modern input use and crop diversification choices.

*3.1.2.2. Environmental indicators*. *Diversity of crops and livestock*: The number (diversity) of crops grown per year per household was highest in the irrigated farm HH type 6 followed by HH type 7 and lowest in the canal irrigated HH type 5 due to the unreliable supply of water for irrigation (Table 3). Availability of family labor, access to institutional borrowing, and farm investments over the last 5 years led HH type 6 to become the most diversified. HH type 2 maintained the highest number of livestock species (cow, buffalo, goat, sheep, etc.).

Level of intensification: HH type 1 followed low input use production systems and derived more than 72% of its total income from off-farm and livestock activities. In contrast, HH type 7 with access to bore well irrigation practiced input-intensive production systems. The level of fertilizer application ranged between 0.2 and 1.6 kg/ha for rainfed farm HH types 1–4 and between 18 and 116 kg/ha for the remaining three irrigated farm HH types. Application of manure also varied significantly between rainfed farm HH types (60 to 156 kg/ha) and irrigated farm HH types (122 to 3617 kg/ha). It is interesting to note that HH types 2 and 5 consisting of a larger proportion of marginal landholders (Fig. 6) derive sustenance through livestock and irrigation.

*Yield variance*: Yields of major crops and their variability (coefficient of variation) across farm HH types varied (Table 5), with HH type 7 recording the highest yields and HH type 1 the lowest. Crop yields as well as yield variability varied significantly both among rainfed HH types (1–4) and irrigated HH types (5–7). The absolute crop yields of millets and legumes in the irrigated HH types 5 and 6, however, were comparable to some of the rainfed HH types. HH type 7 had the least crop yield variability which could be due to assured irrigation, diversification, and higher input use.

### 3.2. Participatory identification of constraints and potential interventions

For each of the seven farm HH types, we first prepared a list of context-specific constraints that hinder agriculture production and livelihood opportunities in consultation with multiple stakeholders. The participatory ranking of constraints across farm HH types is presented in Table 6. Crop loss attributed to decreasing length of growing period due to delayed onset of monsoon was one of the most important constraints across all HH types. However, this constraint is assigned a much higher rank by HH types 2, 4, 6, and 7. Low income levels, high risk associated with agriculture, and poor groundwater quality were the biggest constraints for HH type 1. Pests and disease management ranked high on the constraints list of HH types 5 and 7. For HH types 2, 3, and 4, fodder scarcity and livestock mortality were the top constraints. Crop damage by stray animals and declining crop productivity under khadins (runoff-fed cultivation) were the highest ranked constraints for HH type 3. Farmers in HH type 5 ranked termites, weed infestation, and irregular supply of canal water as their top constraints.

In consultations via Innovation Platforms and with village development committees, expert stakeholders and farmers, potential interventions for sustainable intensification across each of the farm HH types were identified. Participatory prioritization of the interventions suggests that diversification using short-duration cultivars of millets and legumes, livestock intensification, and integration of perennial system components such as horticulture and forestry ranked high on the priority list across all farm HH types.

Integration of perennial system components ranked high on the priority list of a majority of HH types. Resource poor, woman-headed households that constitute farm HH type 4 had a greater preference for integrating perennials as well as small horticulture kitchen gardens that serve both market demand and their domestic consumption needs. HH type 2 also ranked the same intervention as their top priority, but purely driven by a market-oriented production approach.

**Table 5**
Grain yield and co-efficient of variation (CV) of major crops across farm types.

| Crop | Farm type 1 | | Farm type 2 | | Farm type 3 | | Farm type 4 | | Farm type 5 | | Farm type 6 | | Farm type 7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Yield | CV | Yield | CV | Yield | CV | Yield | CV | Yield | CV | Yield | CV | Yield | CV |
| Pearl millet | 360 | 80 | 493 | 63 | 610 | 20 | 361 | 74 | 685 | 31 | 747 | 51 | 1045 | 20 |
| Cluster bean | 493 | 64 | 631 | 44 | 560 | 36 | 575 | 49 | 590 | 36 | 643 | 40 | – | – |
| Chickpea | – | – | – | – | 712 | 30 | 640 | 18 | 925 | 46 | – | – | – | – |
| Wheat | – | – | 1000 | 17 | 619 | 9 | 981 | 55 | 1634 | 25 | 2005 | 29 | 2511 | 22 |
| Mustard | – | – | – | – | 750 | 28 | – | – | – | – | 1035 | 34 | 1311 | 13 |

**Table 6**
Prioritized constraints and possible interventions identified jointly with farmers.

| Constraints | Farm type 1 | Farm type 2 | Farm type 3 | Farm type 4 | Farm type 5 | Farm type 6 | Farm type 7 |
|---|---|---|---|---|---|---|---|
| • Local millets and legumes not maturing due to delayed onset of monsoon-(water scarcity)/ low yielding seeds of crops | 3 | 1 | 4 | 1 | 4 | 1 | 1 |
| • Fodder scarcity / low biomass in common pasture | 4 | 2 | 3 | 2 | 7 | | |
| • High morbidity and mortality in livestock due to disease & pests | 5 | 3 | | | 4 | | |
| • Dilution of cattle breed and no demand for males - low income | | 6 | 7 | | | 6 | |
| • Declining crop productivity under khadins | | | 2 | | | | |
| • Termite and other pests in cluster bean, chickpea, and other crops | | 9 | 5 | 4 | 1 | 5 | 3 |
| • Soil degradation- soil erosion/ poor soil health | | | 6 | | 5 | 4 | 5 |
| • Low income and high risk in agriculture | 1 | 7 | 8 | 3 | 6 | | |
| • Poor quality of underground water for crops and drinking | 2 | 8 | 9 | 5 | | 7 | 2 |
| • High infestation of weeds in chickpea | | | | | 3 | | |
| • Irregular supply of canal water/declining groundwater | | | | | 2 | 2 | 4 |
| • High labor cost | | | | | | 3 | 5 |
| • Low market price for small ruminants, food grains and fruits | 7 | 5 | 9 | 6 | | | |
| • Crop damage by wild/stray animals | 6 | 4 | 1 | 7 | | 8 | |
| ***Identified interventions (opportunities)*** | | | | | | | |
| • Improved and short-duration varieties of millets and legumes (access to seed) | 2 | 1 | 1 | 5 | 2 | 1 | 1 |
| • Prophylaxis in livestock – service providers | 6 | 4 | 6 | 2 | 4 | | 4 |
| • Participatory development of pasture on common land/fodder bank | 7 | 3 | 5 | 4 | | | |
| • Intensification of Khejri as agro-forestry | 1 | 7 | | | | 6 | 7 |
| • Seed treatment in chickpea and cluster bean | | | 2 | | 1 | | |
| • Few horticultural plants for each family (near homestead) | 8 | | | 3 | | | 6 |
| • Grading up of goats and linking to market | 4 | 5 | 3 | 1 | | | |
| • Gum production enhancement in *A. Senegal* | | 7 | 7 | | | 7 | |
| • Integrating rainfed herbs/horticulture + micro irrigation + rainwater harvesting in rainfed systems | 5 | 2 | | | 3 | 3 | |
| • Efficient recycling of waste (FYM/composting) | | 10 | | 8 | 9 | | |
| • Castration of male cattle and their collective marketing | | 6 | 4 | | | | |
| • Soil test-based fertilizer application | | | | | 6 | 2 | 3 |
| • Integrated weed management | | | | | 5 | | |
| • Plant protection | | | 7 | | 7 | 3 | 2 |
| • Village level seed production | | | | | 8 | 4 | |
| • Rainwater harvesting for drinking - Tanka | 3 | 9 | 8 | 6 | | | |
| • Small farm mechanization | | 8 | | | | 5 | 5 |

Prioritization was done on a 1–10 scale, where 1 is the highest priority and 10 the lowest priority by consensus.

Intensification of a system based on the multipurpose leguminous forestry tree Khejri was of the highest importance to HH type 1. Horticulture integration was a top priority for HH types 5 and 6, who both have access to irrigation and labor. The priority ranking of interventions also varied across study sites. For example, only in Barmer district did the cultivation of native medicinal herb Shankhpushpi (*Convolvulus pluricaulis)* rank high on the priority list for farmers belonging to HH types 2 and 1. Intensification of farming systems with small ruminants ranked high among the rainfed HH type 3 farmers. Interventions relating to goat rearing and prophylaxis in animals ranked high on the priority list of woman-headed HH type 4. The farmers' highest priority in HH type 5 was capacity building on seed treatment, prophylaxis in livestock, access to seed of short-duration varieties, and integration of profitable perennials.

### 3.3. Ex-ante impact of selected potential interventions

Results from the participative prioritization of potential interventions reveal that the integration of perennial components into existing farming systems garnered greater interest among a majority of stakeholders. We co-designed four major interventions following this exercise and performed ex-ante assessments of these to inform multiple stakeholders of the potential costs and benefits of adopting the same. The four major interventions are: integrating (i) Ber or (ii) Gonda horticulture crops into existing farm systems on 1 ha with 6 m × 8 m to 10 m × 10 m spacing, respectively; (ii) fifty plants of *Senegalia senegal/ Hardwickia binata* planted on the boundary for rainfed HH type 2 as well as irrigated HH types 5 and 6; (iii) intensification of multipurpose Khejri trees across both rainfed and irrigated HH types with boundary planting of 25 and 50 trees/ha; and (iv) integrating pomegranate trees in irrigated HH types 5 and 6. Only farm HH types 1, 2, 5, and 6 opted for perennial component systems integration. For rainfed households, every such unit needed greater investment in terms of an underground rainwater harvesting structure (*Tanka*) of 60-70 $m^3$ sufficient for providing supplemental irrigation through drip system for 100–150 fruit trees adapted to these arid regions (Meghwal, 2011). These perennials have an economic life of more than 25 years, but we assumed a moderate project life of 20 years.

Before an ex-ante assessment of the interventions, we calculated net returns per hectare for different crops under existing farming systems (Table 7). It is interesting to note that pearl millet delivers negative net returns in all of the rainfed HH types. Despite negative returns, farmers continue to cultivate it because (i) they do not account for the cost of family labor (US$ 65–105/ha depending on the crop); and (ii) the crop residues are important for maintaining livestock. The net present value

**Table 7**
Net returns (in US$/ha) from different crops across farm types in arid western Rajasthan.

| Crop Name | Farm type 1 | Farm type 2 | Farm type 3 | Farm type 4 | Farm type 5 | Farm type 6 | Farm type 7 |
|---|---|---|---|---|---|---|---|
| Pearl millet | −52.3 | −18.1 | −15.2 | −10.9 | 81.8 | 31.3 | 85.3 |
| Cluster bean | 247.5 | 341.1 | 376.7 | 430.0 | 383.9 | 584.3 | 618.6 |
| Chickpea | – | 289.1 | 236.8 | 65.8 | 274.1 | – | – |
| Wheat | – | 97.6 | 23.4 | 10.2 | 277.8 | 230.3 | 368.0 |
| Cumin | 125.0 | – | 126.4 | – | – | 651.5 | 731.9 |
| Mustard | – | – | 59.5 | – | – | 144.2 | 258.5 |
| Moth bean | 115.4 | 61.5 | – | 39.9 | – | 43.0 | – |
| Mung bean | 46.5 | 125.0 | 50.3 | 160.5 | – | 607.8 | – |
| Mixed crop | 57.3 | 80.5 | 64.1 | 94.5 | 159.4 | 114.3 | 124.3 |

**Table 8**
Net present value (US$/ha) from different crops at existing and potentially increased yields across farm types over 20 years.

| Farm type | Scenarios | Pearl millet | Cluster bean | Chickpea | Wheat | Cumin | Mustard | Moth bean | Mung bean | Mixed crop |
|---|---|---|---|---|---|---|---|---|---|---|
| Farm type 1 | 1.With existing yield | −555 | 2,624 | | | 1,325 | | 1,224 | 493 | 608 |
| | 2. With 15% increased yield | −417 | 3,017 | | | 2,142 | | 1,510 | 801 | 1,105 |
| | 3. With 30% increased yield | −279 | 3,409 | | | 2,958 | | 1,796 | 1,097 | 1,615 |
| Farm type 2 | 1.With existing yield | −192 | 3,617 | 3,066 | 1,035 | | | 652 | 1,325 | 854 |
| | 2. With 15% increased yield | −54 | 4,009 | 3,734 | 2,074 | | | 938 | 1,633 | 1,352 |
| | 3. With 30% increased yield | 84 | 4,402 | 3,491 | 3,124 | | | 1,225 | 1,930 | 1,861 |
| Farm type 3 | 1.With existing yield | −161 | 3,994 | 2,511 | 248 | 1,340 | 631 | | 533 | 680 |
| | 2. With 15% increased yield | −23 | 4,387 | 3,179 | 1,287 | 2,157 | 1,596 | | 841 | 1,178 |
| | 3. With 30% increased yield | 115 | 4,779 | 3,836 | 2,337 | 2,973 | 2,561 | | 1,138 | 1,687 |
| Farm type 4 | 1.With existing yield | −107 | 4,560 | 698 | 108 | | | 423 | 1,702 | 1,002 |
| | 2. With 15% increased yield | 31 | 4,952 | 1,366 | 1,147 | | | 709 | 2,009 | 1,500 |
| | 3. With 30% increased yield | 169 | 5,344 | 2,023 | 2,197 | | | 996 | 2,306 | 2,009 |
| Farm type 5 | 1.With existing yield | 867 | 4,071 | 2,906 | 2,946 | | | | | 1,690 |
| | 2. With 15% increased yield | 1,132 | 4,612 | 3,734 | 3,985 | | | | | 2,295 |
| | 3. With 30% increased yield | 1,398 | 5,152 | 4,561 | 5,035 | | | | | 2,899 |
| Farm type 6 | 1.With existing yield | 332 | 6,196 | | 2,442 | 5,848 | 1,529 | 456 | 6,445 | 1,212 |
| | 2. With 15% increased yield | 597 | 6,736 | | 3,481 | 7,725 | 2,494 | 742 | 6,752 | 1,816 |
| | 3. With 30% increased yield | 862 | 7,277 | | 4,531 | 8,541 | 3,459 | 1,029 | 7,049 | 2,421 |
| Farm type 7 | 1.With existing yield | 904 | 6,559 | | 3,902 | 7,761 | 2,741 | | | 1,318 |
| | 2. With 15% increased yield | 1,170 | 7,100 | | 4,941 | 8,577 | 3,706 | | | 1,922 |
| | 3. With 30% increased yield | 1,435 | 7,641 | | 5,991 | 9,394 | 4,672 | | | 2,527 |

over a 20-year period for different crops at existing and potentially increased yields are reported in Table 8. These results were then compared with the results from the ex-ante assessment of alternative land use system interventions.

A total of four different interventions that involved the integration of horticulture and forestry were evaluated for both rainfed farm HH types 1 and 2 and irrigated HH types 5 and 6. Pomegranate-based horticulture system integration was evaluated only for irrigated land households. As highlighted in the participatory prioritization of potential interventions, intensification of Khejri trees in existing farms that ranked as the highest priority for rainfed HH types delivered the highest IRR. When we considered a discount rate of 8%, calculated NPVs from the alternate agro-horticulture/agro-forestry systems were four times higher than those of the existing farming system crops in both farm HH types 1 and 2 (Tables 8 and 9). For the irrigated HH types 5 and 6 however, the NPVs from Ber- and Gonda-based system integration were two times higher than those from existing farming system crops. The irrigated farm HH types have the highest potential to increase income by about five times through the integration of pomegranate-based systems. The sensitivity analysis demonstrates that the suggested agro-horticulture options would become more profitable if the discount rate is lower at 6%. However, these options would still remain economically viable even if the discount rate (interest rate) is increased to 10%. Table 8 describes the scenarios which indicate that the potential increase in the yield of existing annual crops by 15% and 30% though would significantly increase their net present value, but the potential net returns from the alternative agro-horticulture system (Table 9) would still be comparatively much higher.

## 4. Discussion

We developed farm HH typologies based on a hypothesis that relates the main features of agriculture in western Rajasthan, multi-stakeholder assumptions, and theories on existing farm structural and functional traits, and livelihood strategies in the local context to differentiate farm households and design targeted interventions. Integrating participatory and statistical techniques that take into account multiple features like livelihood assets, resource endowments, production objectives, and other factors, smallholder farmers of the dryland regions of western Rajasthan were clustered into seven farm household types. Our analysis provides evidence that household farm systems could be better characterized and grouped together by incorporating a number of structural and functional features of such systems rather than relying on just one resource endowment i.e., land size. Multiple stakeholders including farmers (through FGDs and IP meetings) who are embedded in the target population with local community knowledge participated throughout the typology construction and validation process. Involving local stakeholders in the research process generated insightful feedback and acceptance of the usability of results. Typology validation with the stakeholders resulted in more than 90% of the participants endorsing

**Table 9**
Net present value (in US$/ha) from different alternate land use systems over 20 years.

| Alternate land use system | Scenarios using alternative discount rates (%) | Rainfed farm household types | | | | Irrigated farm household types | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Initial investment | NPV-20 yrs | IRR | Payback period (years) | Initial investment | NPV-20 yrs | IRR | Payback period (years) |
| Gonda-based system | 6 | | 16,727 | 20 | 6 | | 18,884 | 30 | 5 |
| | 8 | 2,371 | 12,634 | 18 | 6 | 1,161 | 14,580 | 28 | 5 |
| | 10 | | 9,552 | 16 | 6 | | 11,341 | 25 | 5 |
| Ber-based system | 6 | | 15,120 | 19 | 6 | | 20,739 | 32 | 3 |
| | 8 | 2,532 | 11,924 | 17 | 7 | 1,161 | 16,058 | 30 | 4 |
| | 10 | | 7,940 | 15 | 8 | | 12,533 | 27 | 5 |
| Pomegranate | 6 | | | | | | 65,547 | 47 | 3 |
| | 8 | – | – | – | – | 1,887 | 51,419 | 44 | 3 |
| | 10 | | | | | | 40,758 | 41 | 3 |
| Khejri (+25 trees) | 8 | 32 | 1,790 | 29 | 8 | 32 | 1,790 | 29 | 8 |
| Khejri (+50 trees) | 8 | 65 | 3,637 | 29 | 8 | – | – | – | – |

the identified farm HH types.

Overall, farm HH types differed widely in various structural and functional resource endowments: land size, access to credit, irrigation availability, technology access, production orientation and objectives, education, experience, management practices, and skills (Crowley and Carter, 2000) and their attitudes towards risk (Salasya, 2005), altogether shaping their specific agricultural production and livelihood strategies. Rainfed farm HH type 1 and woman-headed farm HH type 4 are the most marginalized among the seven clusters practicing low input-low output subsistence agriculture production systems. Between these two resource-poor household groups, the woman-headed HH type 4 achieved higher crop yields than HH type 1. It is of significance to note that while most of the agricultural activities were managed by women in HH type 1 as well, the decision making power remained largely with the male members, unlike in the woman-headed HH type 4. This highlights the importance of establishing gender equity in household decision making to enhance agricultural productivity. Agriculture was a low priority activity for the two HH types 1 and 4 which constituted a total of 36% of the survey households. Higher dependence on off-farm income in both HH types 1 and 4 could have limited their resource allocation towards crop production activities. Although in the long run, off-farm income diversification may become a dominant strategy due to the increasing impact of several biophysical stressors on agriculture productivity, crop production activities and strategies will remain important for food and nutrition security of both households and livestock in the short run for farm HH types 1 and 4. The shift towards higher dependence on off-farm income was evident in resource-rich irrigated farm HH type 5. Such income diversification strategies to offset crop income risk can affect decision making in agriculture production, shifting priorities in resource allocation.

Numerous farm typology studies that incorporate statistical and/or participatory methods aim at exploring typology-specific opportunities based on the focus and objectives of research (Kuivanen et al., 2016; Andersen et al., 2007). Identified opportunities, although technically feasible, may be hampered by other constraints or priorities that may emerge when considering the farm level. Therefore, before exploring designing interventions, it is very important to engage in a participatory learning process involving local experts, policy makers, and farmers to identify such constraints and priorities that are shaped by specific local and household contexts. With a view to bridging this gap in literature, we engaged in a participatory learning process with multiple stakeholders who identified and prioritized household type-specific constraints and potential interventions to enable sustainable intensification of farming systems. Based on these learnings, we participatively implemented context (farm HH type)-specific prioritized interventions for 50–100 farmers in each of the locations directly, and indirectly for about 200 farmers nearby (Dryland Systems, 2015) (Results from the on-farm assessments are not part of this paper). Categorizing households into farm household types was useful not only to better target agricultural innovations but also to understand how the specific objectives and endowments of different household types affect resource allocation (Zingore et al., 2007; Riveiro et al., 2013).

The priorities of irrigated farm HH types and rainfed farm HH types varied significantly. While rainfed farmers focused on livestock and fodder augmentation, irrigated farm HH types were interested in crop-related interventions that included micro-irrigation, integrated fertilizer and pest management, and village-level seed production opportunities. However, access to improved and short-duration cultivars of both millets and legumes was unanimously a top priority for all the HH types except the woman-headed HH type 4. Apart from insights into the local context, our understanding of the diversity of the households and their constraints allowed us to place these results in context. Farmers know they need to adapt to changing climate and altered growing conditions and are looking for interventions that incorporate climate-resilient features. Another interesting result from this study relates to gender attitudes towards farming. The woman-headed resource-poor HH type 4 who are predominantly engaged in goat rearing favor homestead gardening over access to improved cultivars. Home gardens contribute to both nutritional and economic outcomes and could contribute to a greater agency for women farmers and eventually lead to greater gender equity. Irrigated farm HH types did not show interest in participatory development of fodder banks or common pasture lands. Fodder deficit, however, was a major constraint for almost all the rainfed HH types. Developing a small ruminant i.e., goat value chain that effectively links them to markets and service providers also ranked high on the list of rainfed farm HH types. Results from these findings led to the co-designing of two major interventions: development of a small ruminant value chain and fodder augmentation through common silvi-pastures. The women members provided a leadership role in the interventions on goat value chain development and actively participated on a women's sub-committee to manage harvesting and sharing of fodder from the community silvi-pasture systems rehabilitated as part of the CGIAR Research Program on Dryland Systems.

There is strong evidence that hardy perennials, especially integrated systems based on Ber, Gonda and Amla together with legume intercrops under rainfed systems or pomegranate and lemon under irrigated systems could increase net returns, stabilize farm incomes, and minimize land degradation (Pareek and Awasthi, 2008; Meghwal, 2011; Singh and Kumar, 1993; Kumar et al., 2016) in arid Rajasthan. Intensification of local multipurpose trees Khejri and Kummat (*Senegalia senegal*) have shown potential to enhance farm income and resilience (CAZRI, 2010; 2011). These alternative land use systems can help smallholder dryland farmers to cope with feed and fodder scarcity.

We did an ex-ante evaluation of such integration and intensification of perennial components to objectively inform all stakeholders on the potential costs and benefits of adopting such interventions. The ex-ante analysis demonstrated substantially higher net returns from the agro-horticulture system and intensification of Khejri-based agroforestry system across farm types both under rainfed and irrigated conditions as compared to existing crops. Integrating farmer-preferred fruit trees into the existing farming system has the potential for additional annual net returns of up to US$ 500/ha. The additional benefit of US$ 139 from intensification of Khejri as part of agroforestry systems with 50 tree/ha could be higher if farmers use their own labor. Khejri, which is known as the lifeline of the desert, also provides nutritious fodder for livestock, conferring dual benefits. Moreover, it contributes to carbon sequestration to the tune of 0.63 to 0.85 tons/tree (Rathore and Jasraj, 2013). A long term experiment at Jodhpur (Bhati and Faroda, 1998) demonstrated that pearl millet yield significantly increased in the Khejri-based agroforestry system as compared to the control. Each tree resulted in 2.6 kg incremental production of pearl millet besides fodder, pods, and twigs, providing additional benefits of US$ 5.5 per tree every year. The increase in yield could be due to a combination of extra nutrients from nitrogen fixation and shading during hot summer. A hectare of Ber-based agro-horticulture system can provide year-round supply of fodder for five small ruminants and fuelwood for a family of four, besides efficient nutrient cycling, and increase in economic stability (Faroda, 1998). Gupta et al. (2000) reported that a 3-year-old plantation of 400 Ber plants/ha in association with green gram performed well with seasonal rainfall of 210 mm; fruit yields from the intercrop increased net profit significantly. Intercropping in newly planted Ber orchards had no adverse effect on plant growth for up to 5 years and exhibited higher yields of the intercrop (Sharma and Gupta, 2001). The potential integration of pomegranate resulted in the highest NPV among all other interventions. The ex-ante assessment results were shared with farmers during participatory prioritization, which could better inform the farmers on the viability of different options and helped convince them of the potential of agro-horticulture and agroforestry. As a result, thirty-two farmers from four farm HH types (1, 2, 5, and 6) opted for integration of different horticulture and forestry species as per their priority (Table 6) as part of CGIAR Research Program on Dryland Systems. However, handholding of farmers in the initial stages remains important for the successful adoption of alternate land use systems.

## 5. Conclusions

We presented a flexible methodological framework integrating participatory and statistical methods to characterize farm household typologies. We demonstrated how participatory tools can help consolidate the complexity of local circumstances and are useful in identifying and prioritizing locally appropriate technology interventions for different farm household types. Our results suggest that research for development programs must tailor their development strategies, interventions, and policies by accounting for the heterogeneity and complexity of target communities to increase innovation adoption under dryland systems.

We employed a mixed-method approach to capture the complexity and diversity of smallholder farming systems in western Rajasthan to co-design effective interventions for sustainable intensification. Various policy recommendations can be drawn from this study. Our results make a strong case for revisiting one-size-fits-all policy interventions and move towards locally appropriate targeted interventions. This is particularly applicable for the drylands where resource endowments are unequal and household objectives are diverse. Our results suggest investments in gender equality and agency can achieve multiplier effects. Policies towards supporting diversification strategies such as livestock integration should aim at increasing access to common pool resources. Those able to integrate perennial components should be supported, especially farmers with low landholdings. However, it is also important to consider market level constraints and opportunities to ensure sustainable livelihoods. Results from our exercise can also be used to generate insights on potential complementarities between farm household types to create farmer networks that enable material flows, market linkages, and exchange of experiences and skills.

This study makes two key contributions. First, it establishes the utility and need for adopting multiple livelihood assets-based categorization of farm households to inform targeted interventions in the drylands. Secondly, it demonstrates a practical and integrative application of farm household typology analysis with an iterative participatory process and ex-ante impact assessment to co-design context-specific interventions targeting sustainable intensification. Going forward, to operationalize and scale-up this approach, a matrix of key livelihood assets generated via a digital short survey could be used by development actors to develop homogenous farm household types to rapidly target interventions.

## Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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## Appendix 1 Focus livelihood capital and their indicators

| Natural capital | | |
|---|---|---|
| Total cultivated land (ha) | Cost of livestock maintenance (INR) | Access to common property resources (scale) |
| Cultivated land, shared cropping and rented (ha) | Livestock feed source (type by %) | Cultivated crops and productivity (kg/ha) |
| Other owned land (ha) | Limitations of livestock production (ranking 1-8) | Application of inorganic fertilizer (kg/ha) |
| Livestock owned (in no. by species and age group) | Access to water (no by type) | Application of organic fertilizer (kg/ha) |
| Livestock productivity (e.g.milk, litre/day) | Quality of water (good, average, bad) | Expense on herbicide (INR) |
| Livestock mortality (no.) | Irrigated area (ha) | Limitations of crop production (ranking 1-8) |
| Human capital | | |
| Household members (no by age) | Level of education of household head | Other skills (yes, no) |
| Age of the household head (no.) | Numbers of years in farming | Livelihoods strategies (crop, livestock, off farm, combination) |
| Financial capital | | |
| Expenditure by type (%) | Access to credit (borrowed, INR) | Savings (INR) |
| Major sources of income (%) | Subsidies and insurance (yes, no) | |
| Physical capital | | |
| Access to input market (yes, no) | Access to production facility - machinery (yes, no) | |
| Access to production and processing facility -veterinary support unit (yes, no) | Access to production facility - farm implements (yes, no) | |
| Social capital | | |
| Caste category | Social networking - water user group (yes, no) | Social networking - self-help group (yes, no) |
| Social networking - producer group (yes, no) | Social networking - civic group (yes, no) | Social networking - credit micro finance group (yes, no) a |

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