Exploring agricultural transitions in drylands: A study of smallholder farming systems development in Telangana, India

Bhavana Rao Kuchimanchi

Propositions

1. Intensification and specialization of agricultural production only will not translate into prosperity for farming households.
   (this thesis)

2. Traditional knowledge is the essential basis for genuine sustainable intensification of farming in dryland ecosystems.
   (this thesis)

3. Mixed methods research is essential to comprehend complex and dynamic systems.

4. Veganism will be a necessity, not a fad, in the coming future.

5. “Green” innovations are better discovered than invented.

6. “Win-win thinking” is pernicious to sustainable transitions.

Propositions belonging to the thesis, entitled

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Dedicated to my 91-year-old maternal grandmother,

G. Arundathi Devi

Contents

Chapter 1

General Introduction

1. Background

1.1 The global context

Dryland regions globally span more than 3 billion hectares (ha), covering up to 46.2% (±0.8%) of the global land area (Prăvălie, 2016; Koutroulis, 2019). These regions are home to around three billion people (van der Esch et al., 2017), of which 90% live in developing countries (UNEP, 2011). The United Nations Environment Program (UNEP) defines drylands according to an aridity index (AI) as the ratio between average annual precipitation and potential evapotranspiration. All lands with an AI of less than 0.65 are classified as drylands. Drylands are further classified into hyper-arid deserts (<0.05 AI), arid regions (0.05–0.20 A.I), semi-arid regions (0.20–0.50 AI), and dry sub-humid regions (0.50–0.65 AI). These regions are characterized by low rainfall and high evaporation, resulting in a lack of water and soil moisture. Intensive agricultural activities in such regions can easily lead to soil exhaustion, groundwater depletion, and soil salinity caused by excess irrigation under poor drainage conditions. Therefore, these factors limit crop, forage, and wood production potential. In all, such regions are considered ecologically fragile (Gajbhiye and Mandal, 1983; Millennium Ecosystem Assessment, 2005). In addition to biophysical challenges, dryland regions face societal challenges, such as unequal access to resources, low political support levels, and limited access to knowledge about, e.g. sustainable agricultural technologies (Robinson et al., 2015).

Dryland regions are diverse and have a range of land-use systems, e.g. annual croplands, plantations, forests, grassland areas, natural pastures, fallow lands, and vegetable gardens (FAO, 2000). Crop production is highly dependent on precipitation since irrigation opportunities are generally limited. In such low-productive environments, livestock production is a vital activity that sustains livelihoods (Koohafkan and Steward, 2008). Thornton et al., (2007) and Hodges et al., (2014) stated that livestock production systems in dryland regions have evolved based on the opportunities provided by the existing natural resource base. Hence, livestock in these production systems plays a role that goes beyond food production by providing households (HHs) with manure, fuel, transport, and other by-products for living. Livestock also acts as a safety net for the poor and contributes to farm diversification (Ali, 2007; Kumar and Singh, 2008; Herrero et al., 2013; Gathorne-Hardy, 2016).

Livestock production in dryland regions is predominantly a mobile grazing-based production system. Mobility is a strategy adopted by livestock keepers to cope with constraints and risk (Thornton et al., 2007). It is also considered more economically and ecologically compatible than sedentary systems, as the animals can search for and access feed and water in case of shortages (Nori et al., 2008; IIED, 2010; Notenbaert et al., 2012). Such mobile systems also provide ecological benefits such as allowing plants to recover from grazing, helping in seed dispersal and germination, and fertilizing the soils, thereby contributing to biodiversity regeneration and breed conservation (Mendelsohn 2003; Marty 2005; IIED 2010; Mathias and Mundy 2010; Notenbaert et al., 2012; Hodges, 2014). However, despite the benefits, mobility in livestock production is decreasing due to agricultural intensification and increasing competition for land resources.

1.2 The Indian context

India has 15 broad agro-climatic zones based on physiography and climate. Among these zones, 69% of the geographic area is classified as dryland, of which 15.8% is arid and 37% is semi-arid (Kalsi, 2007; Figure 1). This diverse climate results in high spatial and temporal variability in rainfall and temperature across the country (Rao et al., 2010a). India has a monsoon regime, with 74% and 10% of the rainfall being contributed by the southwest (June-September) and northeast (October -December) monsoon, respectively. On an annual basis, India receives an average of 1190 mm of precipitation. In India's arid and semi-arid regions, the mean annual rainfall ranges between 400 and 750 mm. The length of the growing season ranges from 60–90 days in the arid regions to 180–210 days in the semi-arid regions (Rao et al., 2015b). The annual precipitation in these regions is lower than the evapotranspiration (CRIDA, 2011). India has various soil types (Inceptisols, Entisols, Alfisols, Vertisols, Mixed soils, Aridisols, Mollisols, Ultisols, and Oxisols). Except for Vertisols, most soils in the dryland regions of India, are coarse-textured, have low soil organic matter concentration and water-holding capacity, and therefore are at high risk of erosion. Crop production in such soils is prone to drought stress and nutrient deficiencies because these soils have low inherent fertility and water infiltration rates.

Dryland regions in India continue to score low on socio-economic parameters, such as low land productivity, a high proportion of the population in the agricultural labor force, low employment opportunities, poor infrastructure, and low social developmental indices. Also, the availability of and access to irrigation facilities in these regions is as low as 15% compared to 48% in humid regions. Other socio-economic issues that impact agriculture in these regions are population pressure; fragmentation of agricultural landholdings; farming on leased lands; low investment capacity and credit; lack of proper pricing policy and marketing channels; and low employment opportunities (Harriss-White, 2008; Rao, 2008; CRIDA, 2011; NRAA, 2019).

Despite this, the arid and semi-arid regions of India support 40% of the country’s population and contribute 37% of the country’s foodgrain (Harriss-White 2008; Rao, 2008; Government of India, 2019). In terms of livestock, the arid regions contribute 70% to the agricultural gross domestic product while semi-arid regions contribute up to 40% (Government of India, 2007a). Almost 70% of rural HHs in these regions depend on dryland agriculture for their livelihood, with 82% of farmers being small (1-2 ha land holdings) or marginal (< 1ha land holdings) (CRIDA 2011, Government of India, census, 2011). Further, it is estimated that approximately 77% of India's livestock is kept in extensive systems, which means that they are agro-pastoral, nomadic, and transhumant. In these systems, rural poor households depend significantly on common property resources (CPRs) to raise their animals for their fodder needs (Birthal and Taneja, 2006). CPRs mainly comprise common land resources and water bodies, such as village pastures, community forests, lakes, ponds, and wastelands (Jodha, 1986). These production systems currently produce 74% and 53% of India's meat and milk, respectively (Kishore and Köhler-Rollefson, 2020).

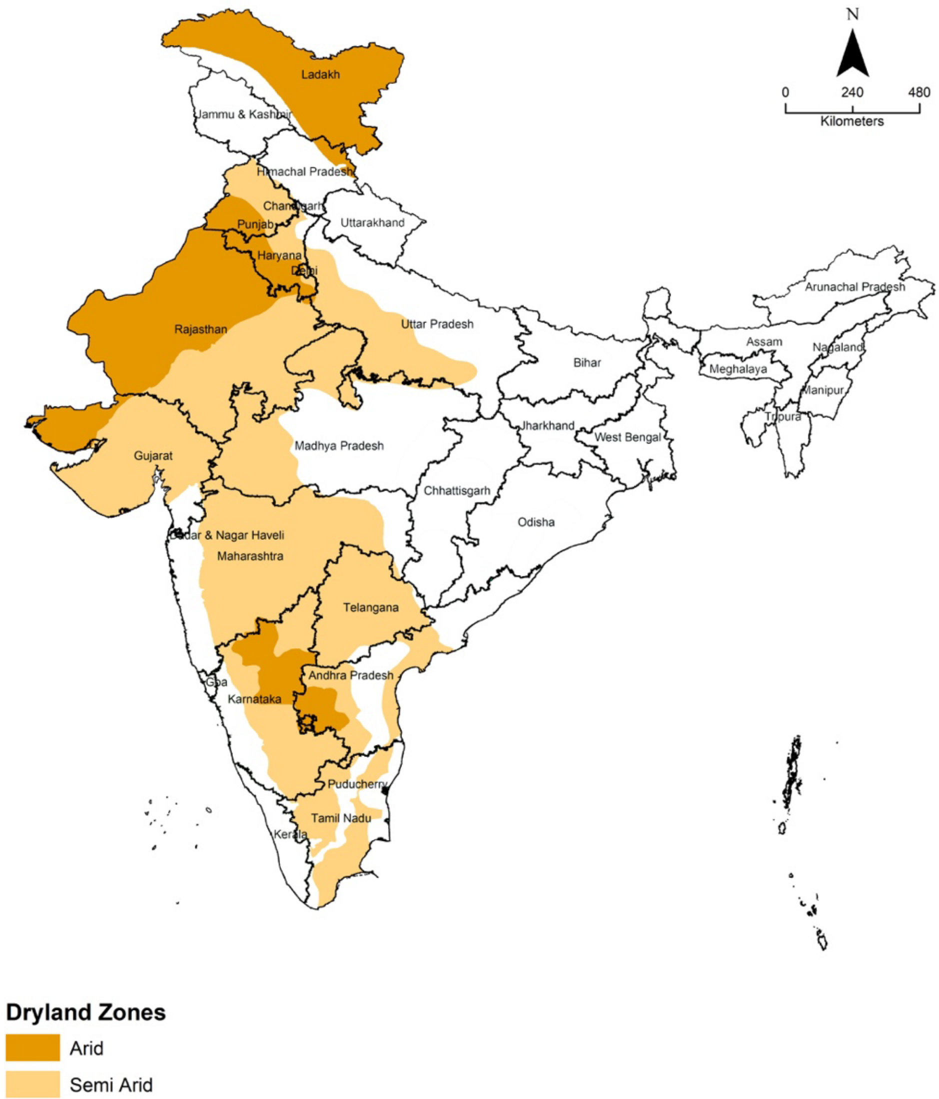

Figure 1: Arid and Semi-arid regions of India

Source: National Bureau of Soil Survey and Land-use Planning, India

Another factor, prevalent only in India, and makes society, economy, and development complex, is the presence of caste segregation, diverse ethnic groups, and uneven regional development, across the country. The caste system is a social hierarchical system with origins in ancient India. This system, however, has been transforming since medieval times by ruling elites and through several social reforms in modern India today (de Zwart, 2000; Bayly, 2001). Despite a tremendous change, stratification continues to exist in various forms. In modern India, according to the Government, the numerous castes are categorized into four main groups, i.e. forward castes (FC), backward castes (BC), scheduled castes (SC), and scheduled tribes (ST). According to Mosse (2018), caste in India is a complex institution simultaneously weakened and revived by current economic and political forces. It continues to contribute to persisting national socioeconomic and human capital disparities along with major impacts on individual well-being. Mosse (2018) adds that the effect of caste is not locational and travels from rural areas into cities and markets and persists because of its advantages and discriminations.

In the Indian rural society (most relevant for this thesis), the picture of the caste system is currently ambiguous. Indications of positive (e.g. higher education, employment opportunities, increase in assets) and negative changes (e.g. socio-cultural discrimination) are seen. This ambiguity is further convoluted because of the numerous ethnic groups within these castes and their relation to agriculture. For example, pastoral groups have distinctive identities, cultures, and traditional knowledge systems, and 46 castes or communities have specialized identities in India (Kishore and Köhler-Rollefson, 2020). These aspects make understanding development and transitions in agriculture complicated.

Despite the significant achievements since the economic reforms in the 1990s, India continues to have vast differences in economic, political, social, and regional aspects. Empirical evidence shows that these disparities have increased in the last two decades due to substantial regional differences in the Indian economy. For example, accelerated economic and social development is more prominent in the southern and western states than in India's northern and eastern states (Kurian, 2007). The rural-urban divide is also increasing, where large and medium cities show exceptional economic and infrastructural growth compared to rural areas in the same region. In the context of the agricultural economy, again a dual impact is seen. On one side, the economic reforms show accelerated economic prosperity and social development in some regions of the country. Simultaneously widespread agrarian distress, farmer suicides, rural unrest, and disproportionate development of socially backward sections and gender also continue to grow (Kurian, 2007; Banerjee and Kuri, 2015).

2. Agricultural transitions in the dryland regions: an overview

2.1 Agricultural transitions and their implications

The increasing demand for crop and animal-source food worldwide has led many developing countries, which are predominantly dryland regions, to transform subsistence crop-livestock systems into intensive and specialized systems with high market-orientation (Thornton, 2010; Tarawali et al., 2011; Udo et al., 2011; Alexandratos and Bruinsma, 2012; Reardon et al., 2019). This transition to intensive agriculture may have enhanced the food output and rural HH incomes, but it also increased competition for already scarce natural resources between HHs in a region as well as between food and feed production (Herrero et al., 2009; Thornton, 2010; Oosting et al., 2014; Herrero et al., 2015).

India has also witnessed widespread agricultural transitions, which started in the 1960s with the beginning of the green revolution (Vishwanathan et al., 2012). These transitions are associated with the intensified land use for crop and feed production, increased use of inorganic fertilizers, and enhanced irrigation for production (Ayantunde et al., 2011; Jayne et al., 2014; Oosting et al., 2014; Pretty and Bharucha, 2014). These farming techniques are further hastened by the increased demand for cash crops, animal-sourced products, and the availability of specific technologies and inputs for production (Thornton, 2010; Tarawali et al., 2011; Udo et al., 2011; Reardon et al., 2019). Although India has achieved self-sufficiency in grain and milk production, agriculture has become resource-intensive, raising severe sustainability issues at the country level regarding increased water stress, desertification, and land degradation (FAO, 2018, Government of India, 2019). Studies by Moni (2009), Pingali (2012), and Thapa et al., (2012) also report that transitions towards intensified crop-livestock production have not benefitted all rural communities in India.

These shortcomings raise questions about the suitability of intensive agricultural systems, with specific reference to the dryland regions of India, as these regions are inherently bio-physically vulnerable. Though considerable research at the farm level about agricultural transitions has been carried out globally (Robinson et al., 2015; Bui et al., 2016), there is limited knowledge about the different facets of agricultural transitions at the farm and regional-level perspectives encompassing social aspects and natural resource use in India. Hence, research in this direction is still needed.

2.2 Agricultural transitions and rural development policy

Agricultural transitions are primarily induced by development policies and programs. In the case of India, development programs with integrated approaches, such as the watershed development programs, have been the foremost driver for agricultural transitions, particularly for dryland regions (Puskur et al., 2004; Sharma et al., 2005, Malik and Bhat, 2014). The governmental investment in this program was about four billion US dollars per year between 2009 and 2012 (Reddy and Syme, 2015) and continues to be a component in a more extensive umbrella program[1] with a similar scale of funding. The aim of the program is to improve the availability of natural resources, enhance agricultural production, create sustainable livelihoods, and capacitate local communities to manage and govern their own resources. The program, since its initiation, has rendered much success in terms of increased availability of water resources, agricultural production, and incomes in dry regions of India (Joshi et al., 2008; Wani et al., 2008a; Palanisami and Kumar, 2009). However, it is unknown and seldomly researched how the watershed development program has impacted Indian society economically, ecologically, and socially. Though some studies by Batchelor et al., (1999); Bouma and Scott (2006); Bharucha et al., (2014) indicate sub-optimal outcomes of these programs. Systemic research on the economic or ecological performance of agricultural transitions triggered by this program in dryland regions in India is still a knowledge gap.

2.3 Intensive and specialized farming systems, water resource availability, and dryland environments

Along with food self-sufficiency, India is also facing rapid changes in agricultural landscapes and increased pressure on groundwater resources. World Bank (2012) states that India is the world's largest groundwater user (230 cubic km/year) and 65% of this groundwater is used to produce half of the country's food (Rosegrant et al., 2009). With a large percentage of land being arid and semi-arid in India, the continued growth of intensive agricultural production in these regions is bound to have several social and environmental implications. Despite a wealth of studies illustrating the detrimental impact of intensive agricultural production on the availability of water resources in India (Jayanthi et al., 2000; Batchelor et. al., 2003; Singh et. al., 2004; Bouma and Scott, 2006; Blummel et al., 2009; Clement et. al., 2010; Haileslassie et al., 2011; Perrin et al., 2012; Barucha et. al., 2014; Ariyama et al., 2019; Singh and Saravanan, 2020) policies and programs continue to promote agricultural intensification as a means of poverty alleviation.

A missing perspective in this context is about the coupled interaction between water used by different farming systems and the water availability within a watershed. This is a critical aspect as watersheds are a social-ecological entity: where the farming systems and people constitute the social component while the watershed and the natural resources comprise the ecological component. Therefore, research that

[1] https://dolr.gov.in/programme-schemes/pmksy/watershed-development-component-pradhan-mantri-krishi-sinchai-yojana-wdc-pmksy

provides insights into farming systems development and their demand for water in a watershed context can mitigate unintended social and ecological effects. It is also expected that such studies could offer opportunities for sustainable intensification of agriculture in dryland regions, where intensification of production is perhaps inevitable.

2.4 Farming systems development in dryland areas and climate change vulnerability

The Central Research Institute of Dryland Agriculture (2011) states that agricultural transitions in dryland regions have increased farmers' vulnerability to climate risks. This is because it has led to lowered soil fertility, groundwater depletion, and a build-up of pests and disease attacks. Agriculture being highly climate-sensitive and with 82% of the agrarian population being small and marginal farmers, addressing vulnerability to climate change is imperative. Such conditions, coupled with volatile markets and the fragile bio-physically environments, make the rural poor most vulnerable to climate change (Banerjee, 2014; Singh et al.,2017; Kuchimanchi et al., 2019) in these regions.

Rao et al., (2019) report that variations in climate (temperature and rainfall patterns) can have more adverse impacts on ecosystem services in dryland regions of India, putting the livelihoods of millions at risk. The authors also state that precipitation variations over the semi-arid regions of India will further intensify the aridity indices highlighting the need for better adaptation and mitigation planning. D'Odorico et al., (2013) and Berg et al., (2016) added that increase in aridity, along with widespread intensive land-use practices, can lead to severe land degradation as it will amplify near-surface climatic changes. Such changes, according to various IPCC reports (2014, 2018, 2019), will enhance water scarcity and food insecurity in dryland regions. Although Adhikari and Taylor (2012) and Singh et al., (2016b) reported that awareness, investments in adaptation, and further development of a national policy to combat climate change has increased - the differentiation from "development-as-usual" programs are still challenging and remains minimal in practice.

Furthermore, though considerable research on various aspects of climate change vulnerability, adaptation, related policies, and livestock and climate change exist for India (Taylor, 2013; Banerjee, 2014; Dubash and Jogesh, 2014; Singh et al., 2014; Udmale et al., 2014; Dhanya and Ramachandran, 2016; Maiti et al., 2017; Kuchimanchi et al., 2019; Singh et al., 2019a; Thornton et al., 2009; Nardone et al., 2010; Thornton, 2010; Alemayehu and Fantahun, 2012; Weindl et al., 2015), there continues to be a knowledge gap on vulnerability research at the farming systems level and the interactions between them and farm development pathways at the regional level. Such research is even more limited in the context of dryland ecosystems.

3. The thesis: The problem statement, conceptual framework, and the chapters

In line with the above, this Ph.D. research explores the various facets of transitions of farming systems occurring in dryland ecosystems as they are inherently biophysically vulnerable. The overall objective of this research, therefore, is to:

"Understand the transitions in farming systems and gain insight into the sustainability implications they have at farm and watershed level, in a dryland region in India."

To achieve this, a set of four sub-objectives are analyzed as follows:

Sub-objective 1: Identify and describe transitions in farming systems in a region in Telangana (India) and their effects on livestock rearing and smallholder livelihoods with particular attention to different caste groups and women.

Sub-objective 2: Characterize the existing farming systems in the region, determine their economic performance and identify explanatory variables of such results.

Sub-objective 3: Estimate the water use of the existing farming systems in the region and assess their impact on water resource availability at a watershed level.

Sub-objective 4: Explore the vulnerability, farming strategies, and farm development pathways of the current farming systems in the region under climate change prospects.

As dryland regions in India have considerable heterogeneity in farming systems (Dikshit and Birthal, 2013) and a social hierarchical system, reliance on a single theoretical perspective would be insufficient. Therefore, a combination of farming systems research (FAO, 2000) and social-ecological systems (SES) theory (Walker et al., 2004) is used as a base for conducting the research. Therefore, a watershed was considered as the social-ecological entity within which the overall objective and the sub-objectives are studied. Figure 2 is a typical map of a watershed indicating the natural drainage lines that carry surface water and sediments on the earth's surface within which social system also exists. The size of a watershed may vary from 500 ha to several thousand hectares, such as the Himalayan watersheds, implying that all ecosystems comprise of watersheds.

To analyze the research objectives, mixed methods—both qualitative and quantitative in combination —were employed to gather the information. Broadly, the methods employed included HH surveys, focused group discussions, timeline

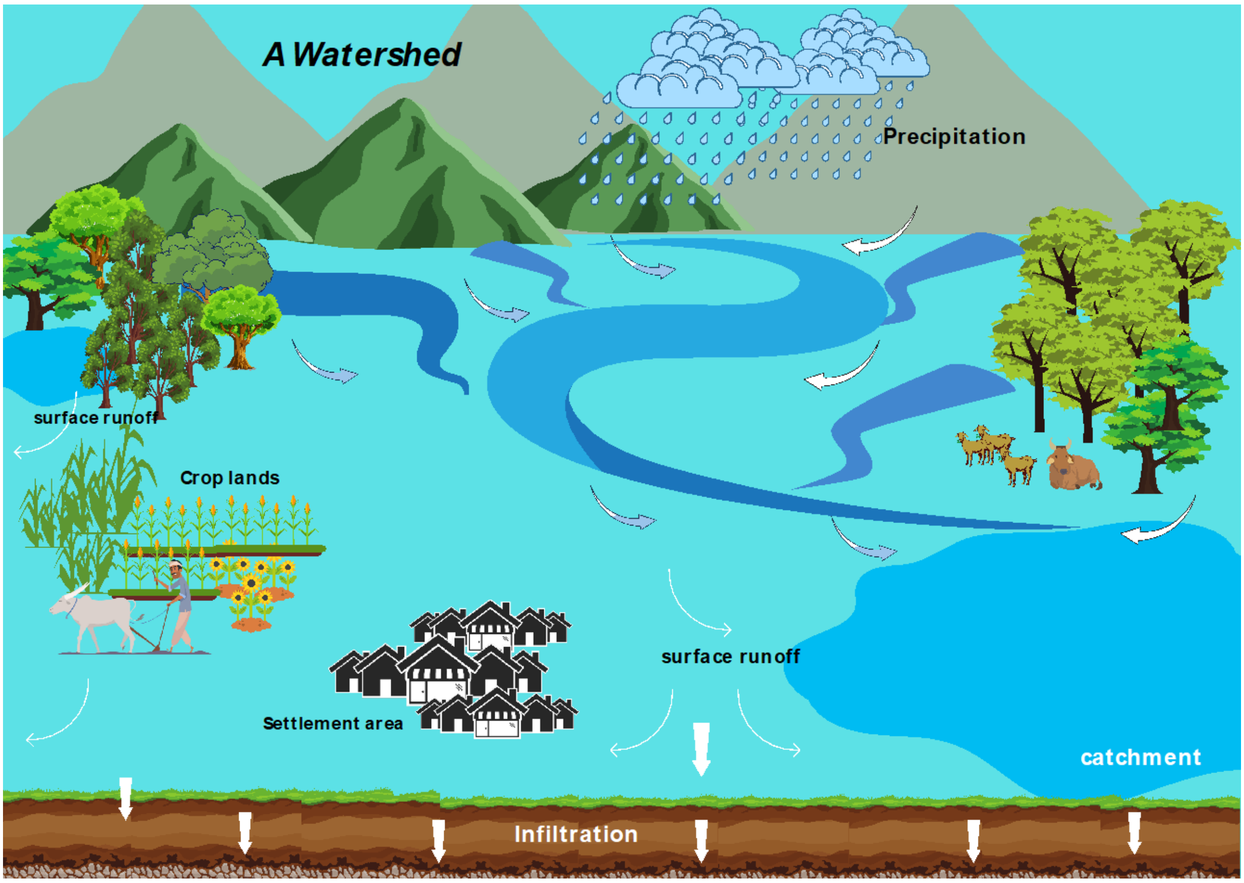

Figure 2: Illustration of a typical watershed

mapping exercises, a longitudinal survey, secondary data collection, GIS methods with ground-truthing to confirm land use land cover changes, and statistical analyses as appropriate.

In ***chapter* 2**, the research starts by mapping farming systems transitions in the study region from 1997 to 2015 and their effect on smallholder livelihoods to set the context. A detailed description of how the transitions occurred and what the key drivers of change are, were identified. The impact of transitions on smallholder livelihoods in general, and particularly on backward caste groups and women was also studied. ***In chapter* 3**, the research was taken further by characterizing the current farming systems and assessing the economic performance of three farming systems that provide consistent agricultural income to the HHs in the region. In this chapter, the outcomes of farming systems transition from a watershed development policy perspective were also discussed. In ***chapter* 4,** a study on the impact of the current farming systems on water availability at the watershed level was undertaken. The social and environmental impacts of these systems in a drylands context were also discussed. Finally, in ***chapter* 5** we gain a deeper understanding of the farm strategies and development pathways of HHs within the three farming systems adopted and their vulnerability to climate change. Finally, in ***chapter* 6,** I summarize the research findings to provide reasoning for why dryland regions may need a paradigm shift in policies, particularly for food production and summarize the outcomes of this research towards sustainable intensification for dryland regions in general.

4. The study site

This research was conducted in a region in the southern state of Telangana, India. In brief, the geographical area of the state is 112,077 sq. km. It is the twelfth largest state in the country in terms of both area and population size. Most of the state's population lives in rural areas, the primary occupation being agriculture; thus, the agriculture sector plays an essential role in the state's economy. The gross irrigated area under crop production is 2,998,798 ha, of which 70% is irrigated by groundwater and 27% by surface water (Government of India Census, 2011). The average agricultural land size holding 1.1 ha in the state, of which marginal and smallholdings constitute 85.9% of total agricultural holdings (Government of India Census, 2011). The major crop in the state is rice, which is the staple. Other crops include maize, sorghum, pulses, groundnut, and cotton. The state also has significant livestock resources and stands 1st in sheep population, 3rd in poultry population, and 9th in buffalo population (20th livestock census, 2019). In terms of water resources, the state is landlocked. Almost 80% of the state is underlain by gneissic complex (hard rock formations), characterized by low infiltration rates, while the remaining area is underlain by a structural fill of sedimentary formations and meta-sedimentary formations. Though the Government of India, Groundwater yearbook (2019–2020) shows an improvement in groundwater levels in the state its availability is still an issue from the agricultural production viewpoint.

For this research, two watersheds were selected in *Rangareddy* and *Nagarkurnool* districts of the State (Figure 3). Both these watersheds fall in different *mandals* (the smallest administrative unit within a district) namely *Talakondapalle* and *Veldanda.* The study watersheds cover 27,814 ha, and 6,572 HHs across seven villages. From this, only 17,164 ha of watershed area and a sample of 3006 HHs were considered for conducting the research. Hence, watershed-1 (WS-1) covers four villages inhabited by 1820 HHs and a total geographic area of 9,463 ha. While the second (WS-2) covers three villages inhabited by 1186 HHs and has a total geographic area of 7,701 ha. Both watersheds fall in the Deccan Plateau and Eastern Ghat agro-ecological sub-region (AESR) 7.2. The climate is characterized by hot and moist summers and mild and dry winters, with an aridity index of $0.2 \leq AI < 0.5$ (Rao et al., 2019) and therefore classified as a semi-arid region. AESR 7.2 is broadly characterized by deep loamy and clayey mixed red and black soils, with medium to very high available water capacity and a growing season duration of 120–150 days (Gajbhiye and Mandal 2000). The districts where the watersheds are located are drought-prone, with an annual rainfall of 500–700 mm.

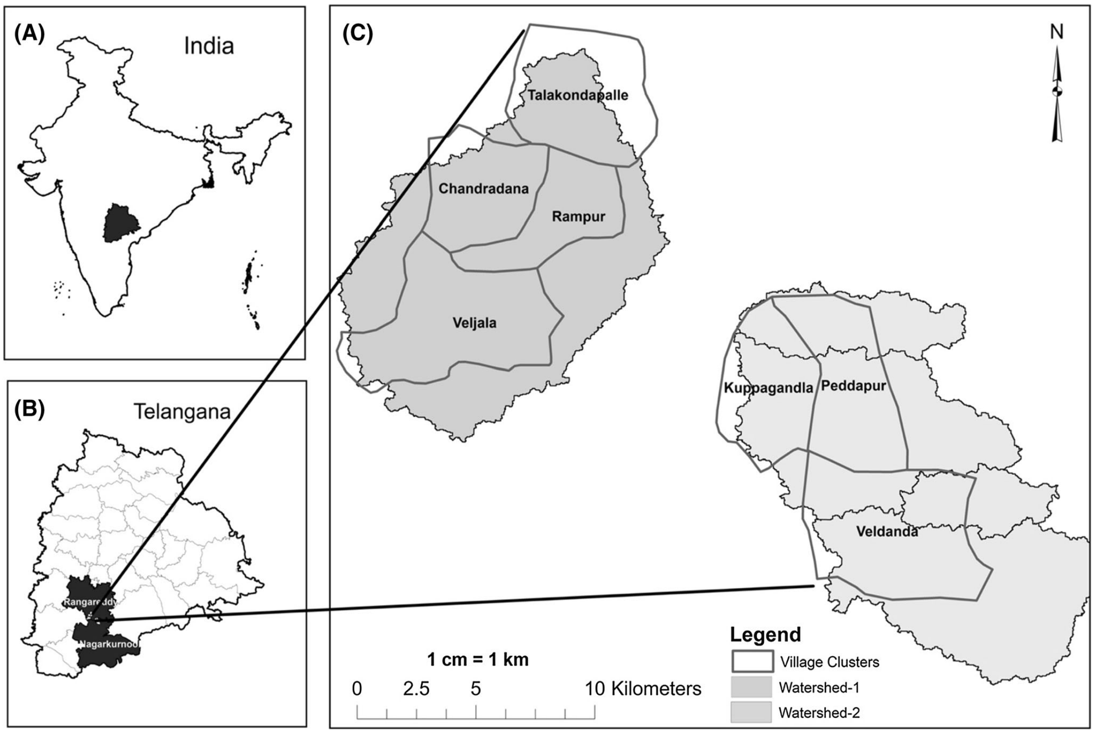

Figure 3: Location map of the study region in India

(A) Location of the state of Telangana in India. (B) Map of Telangana indicating the location of the study districts (C) The two watersheds within which the villages are distributed. Source: ISRO BHUVAN portal (htpps://bhuvan.nrsc.gov.in/bhuvan_links.php, accessed 2016)

Chapter 2

Understanding transitions in farming systems and their effects on livestock rearing and smallholder livelihoods in Telangana, India

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Abstract

Increasing food demands are causing rapid transitions in farming systems, often involving intensified land and resource use. While transitioning has benefits regarding poverty alleviation and food outputs, it also causes environmental and social issues over time. This study aims to understand the transitions in farming systems in a region in Telangana, from 1997 to 2015, and their effect on livestock rearing and smallholder livelihoods. We also examine the impact of the transitions on lower caste groups and women in particular. We collected data using a combination of methods, i.e. a household survey, focus group discussions, and secondary data sources, to build a comprehensive picture of the transitions in the region. We found that subsistence mixed farming systems transitioned to market-orientated specialized systems over a short time span. As the transition process gained momentum, households either intensified their production or got marginalized. Technological interventions, development programs with integrated approaches, and market demand for certain agricultural produce triggered increased regional production but also led to the scarcity of water, land, and labor. The transitions marginalized some of the households, changed the role of livestock in farming, and have been inclusive of both lower caste groups and women in terms of increased ownership of large ruminants and access to technologies. However, for women specifically, further increase in workload in the context of farming is also found.

1. Introduction

Many developing countries have policies to transition from subsistence farming systems into market-oriented systems in response to the increased demand for animal source food. This transition is often associated with the processes of specialization and intensification of farming systems, as well as increased use of resources, such as biomass, land, and water (Tarawali et al., 2011; Alexandratos and Bruinsma, 2012; Bharucha et al., 2014). While such transitions have benefits in terms of increased food output, they may also cause environmental issues, e.g. overexploitation of natural resources, and social issues such as farmer dependency on external inputs and marginalization of communities (Lebacq et al., 2013; Clay et al., 2020).

Agroecosystems in dryland areas, which are predominant regions in developing countries, face harsh agro-climatic conditions and scarce infrastructure and support services, and host diverse farming practices (i.e. pastoral, agropastoral, rainfed, and irrigated crop production). These regions are also hotspots for land degradation, low crop yields, and poverty (van Ginkel et al., 2013; Chander et al., 2014). In India, 69% of the territory is classified as dryland. To develop these regions socio-economically, several development initiatives have been implemented among which integrated watershed development programs (WDPs) have been and continued to be the forefront strategy (GoI 2008; Smyle et al., 2014). WPDs have resulted in the modernization of farming systems in dryland areas. This meant that traditional mixed crop-livestock farming systems, using local livestock breeds and crops, generally transitioned to more intensive market-oriented and specialized farming systems, using imported breeds and new crop varieties (Puskur et al., 2004; van Ginkel et al., 2013; Tian et al., 2014; Amjath-Babu and Kaechele, 2015; Behera et al., 2016; Gathorne-Hardy, 2016). While the transitions in farming systems have increased overall agricultural output (Rao 2000; Government of India 2006; Joshi et al., 2008; Wani et al., 2008; Palanisami and Kumar, 2009), some unfavorable side effects such as the exclusion and marginalization of some social groups (Puskur et al., 2004; Pingali 2012; Kannan 2015), increased workload on women (van Ginkel et al., 2013), and overuse of natural resources (Batchelor et al., 2003; Bharucha et al., 2014) have also been reported.

Development programs like WDPs, which have integrated approaches, are dynamic and known to trigger rapid changes in farming systems that can involve trade-offs and need to be understood further (van Ginkel et al., 2013; Reddy and Syme, 2015) Moreover, research on transitions in farming systems is largely focused on farm-level studies (Robinson et al., 2015; Bui et al.,2016; Gaita´n-Cremaschi et al., 2019). Regional studies of transitions by Dorward (2013), Jayne et al., (2014) Pretty and Bharucha (2014), and DiCarlo et al., (2018) reported how farming systems developed, how they interact during the transitions, and how the transition affected natural resource use. To our knowledge, there are no scientific publications about regional aspects of transitions in India.

Hence, the aim of this study was to understand the transitions in farming systems in a region in Telangana from 1997 to 2015 that has witnessed over three decades of several development initiatives including WDPs. We look closely at how transitions have occurred and their effect on livestock rearing and smallholder farming systems. We also look at the impact of transitions on different caste groups and women.

2. Materials and Methods

2.1 Study location

In this study, a watershed (WS) is considered as the unit of analysis as it is a part of a larger study that looks at the impact of transitions in farming systems on smallholder livelihoods and the environment. This paper is the first study in the series where the WS is not only considered as a hydrological unit but more as a social-ecological entity, which plays a crucial role in determining food, social, and economic security to rural people (Reddy and Syme, 2015). We selected two WSs for the study to understand if the transitions were uniform or if substantial variation existed. WS-1 is in *Talakondapally* Mandal (the smallest administrative unit within a district), covering four villages. WS -2 is in *Veldanda* Mandal, covering three villages. These Mandals are in the *Rangareddy* and *Nagarkurnool* districts of Telangana State (Figure 1). The total geographic area of WS-1 is 14,120 hectares (ha), and the boundary of the villages under study covered 9,463 ha. WS-2 spans 13,694 ha, with 7,701 ha falling within the study village boundary. Hence, for secondary data sources, we considered the boundaries of the villages as the secondary data were aligned more with administrative boundaries than with hydrological ones.

Both watersheds fall in the Deccan Plateau (Telangana) and Eastern Ghat agro-ecological sub-region (AESR) 7.2. This sub-region is broadly characterized by deep loamy and clayey mixed red and black soils, with medium to very high available water capacity, and a growing season duration of 120–150 days. The climate is hot and moist in summer and mild and dry in winters, with an aridity index of 0.2 - 0.5 AI (Rao et al., 2019). Hence, it is classified as a semi-arid region. The districts are drought-prone, with an annual rainfall of 500–700 mm, which follows a seasonal pattern (Gajbhiye and Mandal, 1983).

2.2 Data collection

To achieve the aim of this research, we collected data using multiple methods sequentially to build a comprehensive picture of the transitions and their effects on farming HHs in the region. First, we started with a HH survey to obtain an overview

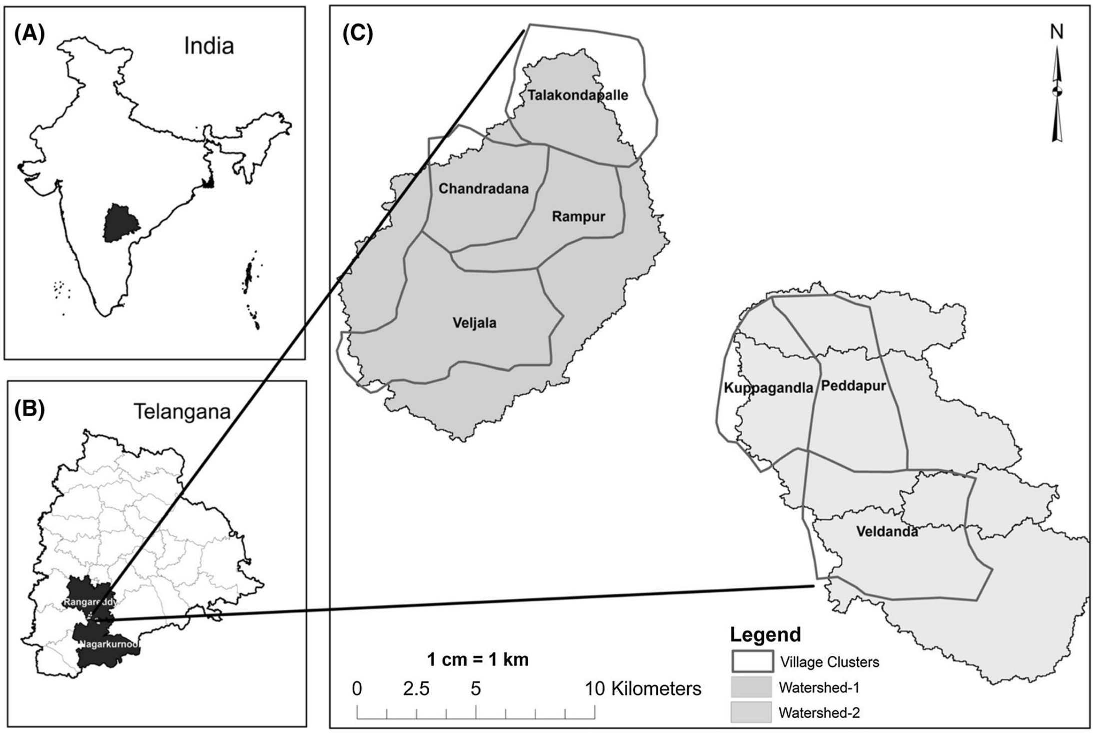

Figure 1: Location map of the study region in India.
A) Location of the state of Telangana in India B) The study region (districts) within the state of Telangana, C) The two watersheds within which the study villages are demarcated. Source: ISRO BHUVAN portal (htpps://bhuvan.nrsc.gov.in/bhuvan_links.php, accessed 2016)

of HHs in the region. The HH survey was conducted in both watersheds covering a sample of 3006 HHs. Surveys were face-to-face meetings with the HH head and were performed using a survey format. The survey provided an overview of information about the population, farm sizes, and categories i.e. large farmers (< 4 ha), medium farmers (2–4 ha), small farmers (1–2 ha), and marginal farmers (up to 1 ha); types of livestock; and different caste groups. The caste system in India is a social hierarchical system that has its origins in ancient India. This system, however, has been transforming since medieval times to several social reforms in modern India today (de Zwart 2000; Bayly, 2001). Although several laws exist, stratification continues to exist in various forms. In modern India, the various castes are categorized into 4 main groups, i.e. forward caste (FC), backward caste (BC), scheduled caste (SC), and scheduled tribes (ST), which were also captured through the survey.

Second, using the above data, seven focused group discussions (FGDs) were organized. The objective of the first FGD was to obtain qualitative information on the overall narrative of how transitions occurred in the region pre-1997 to 2015, along with the drivers of change and its impact on HHs in the region. To achieve this, we selected HHs that had been in the region for the past 30–40 years. This was done in consultation with the head of each village council of all study villages. A village council in India is known as a *Gram Panchayat,* a local self-governance unit. From the list of potential participant HHs, 35 HHs were randomly selected and invited for the FGD. Further, we ensured that all farmer categories and caste groups, along with a representation of members of different age categories, i.e. old (<60 years old), middle-aged (40–45 years old), and young (>25 years old) were present. If the representation of one of these groups/categories was lacking, we substituted a randomly selected HH from the overrepresented group. This FGD was a mixed-gender group, with a total of 37 participants, of whom only four were women. This was followed up by organizing the next five FGDs with HHs belonging to different farming system typologies in the region, identified through the HH survey data (Kuchimanchi et al., 2021c). The aim of these FGDs was like the first FGD in terms of mapping transitions and understanding their characteristics but with specific reference to the farming system. The five farming system typologies were crop without livestock (CWL), crop with dairy (CD), landless with livestock (LWL), crop with small ruminants (CSR), and crop with diverse livestock (CWDL). Within each farming system typology, 30 HHs were randomly selected. Adequate representation from all farm size categories and social groups was ensured. These FGDs were again mixed-gender groups, and the actual participation varied from 25 to 30 members per FGD.

Although women participated in all six FGDs, an additional FGD was organized exclusively with women. Owing to socio-cultural reasons, women in India tend to participate in low numbers or do not voice their opinions in mixed-gender meetings. The objective of this FGD was to get a deeper understanding of how transitions affected women with specific reference to farming systems and practices, as transitions in farming systems could have different impacts on both genders. This FGD was organized as part of a monthly women's selfhelp group meeting in one of the villages, as women of all age groups, castes, and farmer categories are usually present at such meetings. A total of 46 women participated in the FGD.

All seven FGDs lasted for 3–4 h, and the discussions were conducted in the local language, *Telugu*. For all FGDs a participatory timeline mapping tool (Hekkert and Negro, 2009) supported with a list of questions to guide the discussions was used to achieve the objective of each FGD. The key questions in the FGDs were about major changes in farming systems, crops cultivated, livestock reared, fertilizer usage, livestock products, animal health, fodder resources, land use, and water resources. For the five FGDs specific to farming system typologies, questions related to the characteristics of farming systems and changes within each system were discussed. Concerning the impact on caste groups and women, along with the above, additional questions on aspects related to access to resources and challenges faced due to changes in farming systems were asked.

Considering the diversity in social status, farmer categories, caste, and gender in the FGDs, an experienced facilitator was present to moderate the discussions. The facilitator helped avoid domination by the wealthy, elderly, or socially forward groups and provide adequate time to document information in detail. All the discussions were documented on chart papers to maintain transparency and enhance interaction with the participants. As no major differences in narratives were perceived among FGDs, the documented information from all FGDs was summarized into a macro-picture of how transitions took place in the region, highlighting major aspects across a timeline as illustrated in Table 2. Further, the specific impacts on caste groups and women have also been highlighted in Table 2, in the results section and described separately in the subsequent section.

Third, and lastly, to contrast and triangulate the information from the HH survey data and FGDs, we collected secondary government data from both local department offices and online government websites and land use land cover (LULC) evolution in the. The various government data sources consisted of the population census 2001, 2011, crop statistics at the sub-district level between 1996 and 2015, the Agriculture at a Glance-Telangana state report - 2018, statistics from the Agricultural and Processed Food Products Export Development Authority (APEDA), 2019, and livestock census data for 2007, 2012, the Basic Animal Husbandry Statistics, 2019, and the reports of Central Ground Water Boards published between 1997 and 2020. For the LULC evolution analysis, land classes identified and mapped in the study area were according to the National Remote Sensing Agency (NRSA, 2006) as defined below in brief:

- Settlement area: An area of human habitation that has a cover of buildings and basic infrastructure.
- Cropland-irrigated: Cropland under irrigation or lands that are cropped for two or more seasons in a year, as is often associated with irrigation.
- Cropland-rainfed: Cropland associated with rainfed crops under dryland farming with no irrigation (synonymous with areas with the cropping season-extending between June and October).
- Fallow land: Lands that are cultivated temporarily or kept uncropped for one or more seasons but not less than one year.
- Wasteland: Degraded or underutilized land that is deteriorating for lack of appropriate water and soil management but where key functions can be restored.
- Plantations: Areas under tree crops (agricultural/non-agricultural) planted adopting certain management techniques.
- Water bodies: Areas with surface water, e.g. ponds, lakes, and reservoirs or flowing as streams, rivers, canals, etc.

Agricultural crops in India are grown throughout the year in two main seasons. The LULC maps were combined for both seasons in an annual LULC map for the years 1997, 2005, and 2015. For this, only the total geographic area falling within the village boundaries within both watersheds was considered. Before processing the satellite imagery, a ground-truthing exercise was performed to identify samples of different land classes present in the villages using the global positioning system. Details of the data sources for the satellite imagery used are provided in Table 1.

Table 1: Data sources of satellite imagery used for the LULC study

Year	Season	Acquisition date	Sensor	Path row	Resolution (m)
1997	Kharif-monsoon Rabi -winter Zaid -summer	05 October 1997 07 & 20 February 1997 07 April 1997	IRS 1C—LISS III—National Remote Sensing Centre, Hyderabad	100/69	30
2005	Kharif-monsoon Rabi-winter Zaid-summer	01 September 2005 17 November 2005 02 March 2005	LANDSAT- Thematic Mapper (TM)–from USGS[a]	144/48	30
2015	Kharif-monsoon Rabi-winter Zaid-summer	12 October 2015 17 December 2015 03 April 2015	LANDSAT- satellite image operational land imager (OLI) from USGS[a]	144/48	30

[a] Source: http://glcf.umd.edu/data/landsat/

2.3 Calculations and statistical analyses

We performed statistical tests to understand the impact of transitions on certain parameters (i.e. land and herd size) across caste groups and between watersheds. The statistical analyses were performed using the statistical program GenStat (GenStat Committee 2000) using the HH survey data. First, to compare land sizes and herd sizes of HHs between the watersheds, we used the Mann–Whitney U test because the data were not normally distributed. In these cases, the median and 25th and 75th percentiles are reported. The effect of the watershed and caste of the local communities on the variables land size and herd size was analyzed using the generalized linear model procedure, by the model:

$$Y_{ij} = \mu + \alpha_i + \beta_j + \alpha_i \times \beta_j + \varepsilon_{ij}$$

Where Y_{ij} is land or herd size per HH, $_i$ is explained by the mean (μ); watershed i (α_i) and caste j (β_j) are the fixed factors; and ($\alpha_i \times \beta_j$) is the interaction between watershed × caste, and (ε_{ij}) is the residual error.

Pairwise post hoc comparisons between treatment means were done using Fisher's least significant difference method. Dependent variables showed a skewed distribution and were converted to their natural logarithm. To ensure the transformation of values of 0 into natural logarithm, we added one unit to all values. Once the tests were run, the mean values and confidence intervals were then back-transformed (Johnson et al., 1994) and subtracted by one unit. Herd size was expressed in tropical livestock units (TLU). The conversion factors were cattle = 0.7 TLU, buffalo = 1.5 TLU, sheep/goats = 0.1 TLU, and poultry = 0.01 TLU.

3. Results

3.1 Transitions in farming systems from 1997 to 2015

The transition in farming systems described here is a macro-picture of how transitions have occurred in the study region from 1997 to 2015 (Table 2) also with significant events as collected from the HH survey and the various FGDs conducted.

Participants in the first FGD shared that the transitions in farming systems started gradually since 1997, with major shifts occurring after the year 2000. Subsistence mixed farming systems were predominant before 1997, and almost all HHs had livestock then. Crop production was mostly rainfed, while livestock farming was grazing-based. Poultry keeping was mainly with indigenous scavenging birds, and every HH had a few. Farming was subsistence-oriented, and only surplus products were sold at local markets. Irrigated crop farming began in the late 1990s when village electrification and borewell technology emerged. Irrigated crops such as cotton, maize, groundnut, vegetables, fruits, and fodder crops like Napier grass (Pennisetum purpureum) and fodder sorghum replaced rainfed food crops such as castor, sunflower, pearl millet, and native variety of sorghum. These trends could be corroborated by crop production data provided by the agriculture department at the sub-district level for WS-2 (data for WS-1 were not available) for the period of 1996–2015. Major changes were seen in a few crops, e.g. the cropped area under sorghum dropped from 1081 ha in 1996–1997 to 20 ha by 2014–2015. The cultivation of pearl millet was around 103 ha, which completely disappeared by 2015. Similar trends were found for cotton and maize. In 1996, the area under cotton was 186 ha and no maize was cultivated. By 2015, the area under cotton had increased to 1548 ha and 419 ha, respectively. Vegetable cultivation also increased from just 30 ha in 1996 to 245 ha by 2015. The area under fodder sorghum increased from 3 to 38 ha in the same period.

In the same FGD, participants further shared that keeping livestock in the pre-1997[1] period had multiple purposes such as providing food, manure, fuel, and draught power. They mentioned that ownership of good cattle breeds (identified as *Ongole, Deoni, Red Sindhi*, and *Krishna Valley*) was linked to having resources in terms

[1] Livestock population trends pre-1997 at village level could not be triangulated with secondary data due to data gaps, hence trends from 2007 to 2012 only have been presented.

Table 2: Overall narrative of transitions in farming systems from before 1997 to 2015 in the study region

Time-line	Farming systems	Crops	Fertilizers	Livestock	Livestock products	Animal health	Fodder resources	Land use	Water resources
< 1997	Rainfed mixed crop-livestock farming system was the most prevalent. Livestock rearing was grazing based Farming was mostly subsistence oriented	Food crops, e.g. castor, sunflower, pearl millet, and sorghum, dominated	Manure was abundant and was used more than inorganic inputs for crop production	All households kept livestock, and different native breeds existed. Large ruminants were mainly kept by forward castes, while lower social groups reared small livestock. Role of cattle to produce bullocks for draught purposes declined	Wide range of livestock products for HHs and sale at village markets	Disease incidence was low. Use of traditional medicine was prevalent	Common property resources and crop residues were abundant	More common property resources, less land under crop production	Natural water bodies and open wells were the main source. After 1995, borewells emerged due to village electrification
1997 – 2000	Irrigated crop production with borewells started. Farming become more market orientated	New crops and fodder varieties introduced	Subsidies for inorganic crop inputs introduced	Flock sizes of sheep started to reduce specifically impacting the BC caste group	Decline in milk products (e.g. curd, *khoa*, ghee) and wool Focus on milk and meat production started		Grazing restrictions in forests	Wastelands converted to crop lands benefitting all lower caste groups in terms of gaining land for crop production Common property resources start to reduce – impacting all caste groups but poorer HHs and women who reared small ruminants and indigenous cattle	Borewell water available at 18–30 m, which became the main source of irrigation. Open wells declined

2001 – 2006	Farming systems became more specialized, with single species of livestock inclusive of all caste groups Farming systems with no livestock started to emerge	Shift to water-intensive cash crops, e.g. cotton, maize, groundnut, and green fodder crops; reduction in food crops. Mechanization in crop production initiated	Reduction in farmyard manure due to reduction in indigenous cattle per household led to a gradual increase in the use of inorganic fertilizers	Improved and exotic livestock breeds introduced. Increasing trend in milch cattle among all caste groups. Livestock services (fuel and draught) replaced by cooking gas and vehicles	Focus on liquid milk and sale of live small ruminants increased.	New breeds introduced with higher disease incidence. Higher production costs due to the use of modern medicine. More healthcare and insurance available for larger ruminants	Cultivated fodder, post-harvest crop lands, and crop residues became sources of fodder	Increased land under crop production, which continues to expand	Decline in water resources began in both surface and groundwater
2007 – 2015	Shift to specialized livestock farming and semi-intensive system with high market orientation among all caste groups who had access to water	High focus on cash crops and vegetable and fruit production	Shortages of manure due to decrease in livestock per HH. Use of inorganic fertilizers increased	Goat rearing turned into a seasonal activity for all poor HHs irrespective of caste. Sheep and goats being raised on leased lands. Improved and exotic livestock breeds, e.g. Holstein–Friesian and Murrah, replacing indigenous cattle and buffaloes. Native poultry reduced; commercial poultry farms increased	Establishment of government and private dairies increased. New markets for exotic/ crossbred cattle and small ruminants emerged		Increased use of external feed for cattle. Leasing lands for grazing started	Lands converted to other uses, e.g. real estate, increased settlement area, orchards	80% Natural water bodies disappeared. Borewell depth increased to 180–250 m. Leasing of borewells by livestock keepers for water

Source: Compiled from information obtained from seven FGDs with different farmer categories and caste groups conducted in the year 2015. HHs–households of land, water, and finances. Large ruminants were predominantly owned by FCs, while lower caste groups reared small ruminants and poultry. As the mechanization of crop production and motorization of transport increased, the importance of bullocks decreased. Consequently, keeping reproductive cattle to produce bullocks reduced. To this, FGD participants from the CD system added that exotic dairy cattle breeds such as Jersey and Holstein–Friesian started to replace indigenous cattle breeds in 2004 and 2010, respectively. Similar was the case with buffaloes; indigenous buffaloes were replaced by *Murrah* buffaloes since 2002. This trend described in the FGDs was consistent with the government livestock census reports of 2007 and 2012 at the WS level as it indicated a 28% increase in exotic/crossbred cattle and a decrease in indigenous cattle and buffaloes by 40% and 38%, respectively. The participants further added that while changes in breeds increased production and subsequently income, disease incidence in livestock is a drawback. Before 1997, animal disease incidence was low, and the diseases were easily cured with traditional medicines. However, with the introduction of exotic breeds, new diseases were reported, and traditional medicines were no longer useful. While animal health services are present, access to these services was reported to be better for large ruminants than for small ruminants. Insurance schemes are also in place but not considered functional by FGD participants due to low accessibility and laborious processing procedures.

In the case of small ruminants, FGD participants from the CSR system mentioned that changes took place both in terms of flock sizes and rearing systems since 1997. Traditionally, sheep were reared by HHs belonging to a livestock-keeping community called *Gollas* in the state, who are classified as BCs. Sheep rearers in the FGD reported that flock sizes have reduced from 5000 animals per HH in the past to 100–300 animals per HH. The adjustment in flock sizes was dependent on the availability of grazing lands and labor per HH, both of which have reduced over the years. Hence, more HHs keep sheep now than in the past, albeit in smaller flocks. Sheep migration has also stopped and is resorted to only under severe drought situations. *Deccani* was the dominant sheep breed pre-1997. This breed has been replaced with the *Red Nellore* sheep breed from coastal regions since 2000.

Sheep farmers indicated that they prefer *Red Nellore* over *Deccani* as the former gains weight faster despite fodder scarcity. Participants shared that goats were reared by all caste groups but predominantly by women, poor and landless HHs. The breeds reared were native breeds, of which one was extinct, and could not be identified due to a limited database of local breeds in India. In the past, goat rearing was described as a year-round activity by many HHs. It is now a need-based activity for HHs, often done during the summer season or to cope with crop loss, loan repayment, or a sudden need for money. Government livestock census reports from 2007 to 2012 also report a drop-in sheep population (-41%), which could be related to dwindling flock sizes over time, while the goat population shows an increase (26%) as it has turned into a seasonal activity for many HHs. While a general decrease in livestock population is seen at the HH level in the region, whether this change increased the economic value per unit is to be researched upon. Participants in all FGDs indicated that indigenous poultry was kept by all HHs in the past and was an important source of food and income security for the poor, landless, and women. This trend is also indicated by the livestock census where native poultry rearing showed a drop of 82% between 2007 and 2012.

Further, the trends in both crop and livestock production described in all the FGDs do not seem to be limited to the study region but are seen across the state of Telangana. The Basic Animal Husbandry Statistics of 2019 indicate that livestock population changes in the region are similar to the trends at the state level except for sheep and goats which show a substantial increase. This could be due to (i) a lack of data for the study area before 2007 and (ii) small ruminant populations being linked to the presence of certain caste groups or influenced by HH needs. Similarly, concerning the state's cropping patterns, the state's Agriculture at a Glance report indicates a trend towards the cultivation of non-food crops, as the area under food crops came down from 3.39 to 2.62 million ha between 2001 and 2016.

Additionally, participants from different farming systems FGDs reported a change in the kind of livestock products being sold, as the demand for raw milk increased. For instance, traditional farm-processed products like curd, buttermilk, *khoa* (thickened condensed milk), and ghee are not sold by HHs in local markets anymore. This role has been taken over by the government and private dairy units, to which the HHs now supply only raw milk. Moreover, dairy farmers shared that they prefer cows to buffaloes, owing to the better reproductive performance of the former (shorter inter-calving periods), which eventually results in higher income per year. Similar was the case with small ruminants and associated products, particularly for sheep. The demand for wool and other co-products diminished, and sales are currently limited to live animal sale for meat. These trends are aligned with state government data and APEDA, which show a nominal increase in wool production between 2001 and 2015 (i.e. 3.02 to 4.56 million kgs), while the state of Telangana (erstwhile Andhra Pradesh, before 2014) ranks first in sheep production nationally since 2008.

Lastly, Table 3 reports changes in LULC from 1997 to 2015, which further triangulates data from the FGDs. LULC changes indicated an increase in irrigated and rainfed cropland area by 734 ha and 3693 ha, respectively, mainly at the expense of wastelands, which decreased by 5330 ha.

This could be due to an increase in population in the region, as the settlement area has increased from 36 to 475 ha between 1997 and 2015. Further, the reduction in wastelands that were used for grazing livestock resulted in reduced fodder availability for many HHs rearing livestock. This situation worsened further around the year 2002,

Table 3: Changes in land use and land cover from 1997 to 2015 in both watersheds combined

Land classification	LULC 1997 area (ha)	LULC 2005 area (ha)	LULC 2015 area (ha)
Settlement area	36	253	475
Crop land: irrigated	999	2427	1733
Crop land: rainfed	8807	7841	12 500
Plantations	52	612	612
Waste land	7093	5925	1763
Surface waterbodies	177	105	80
	17 164	**17 164**	**17 164**

Source: Satellite imagery from National Remote Sensing Centre - 1997 & LANDSAT -2005 and 2015 (refer to Table1); LULC area is the area within the village boundaries in both watersheds

as grazing restrictions were also levied on nearby forest areas.

Reduction in access to grazing resources along with a sharp increase in cropland, both irrigated (ca. 75%) and rainfed (ca. 40%), not only impacted the availability of fodder for livestock but also livestock rearing in general. Participants from the farming system FGDs shared that currently almost half of the HHs in the villages do not own livestock, also indicated by the HHs survey as 48%. The FGD participants in the CD system stated that dairy producers managed this situation by cultivating perennial fodder crops due to fodder seed subsidies provided by the government and dairy cooperatives. Hence, grazing-based cattle systems eventually changed into semi-stallfed systems, with some grazing on fallow croplands or wastelands if available.

Based on information shared by participants from the CSR system, it is indicated that small ruminant farming transformed into a modern grazing-based system. Earlier, small ruminants were raised entirely on village common lands or wastelands, with surface water bodies as water sources. Now, cropland, orchards, private lands, and borewells for water are leased to rear small ruminants. According to the participants, sheep rearers could find lands to graze their animals more easily than goat rearers, as goats are browsers, and require lands with tree cover. Goat keepers stated that the availability of wastelands with tree cover has decreased considerably. Hence, goats are now reared in small flocks in seasons when crop farming is low or absent or as per need, rather than as a year-round activity as in the past. Small ruminant rearers added that only HHs that could invest in leasing lands and borewells now continue small ruminant rearing with large flocks as a fulltime occupation. The traditional barter systems between small ruminant farmers and crop farmers, where crop residues were bartered against manure, no longer exist.

The participants from all FGDs also stated that while these changes in crop and livestock production took place, water scarcity in the region has also increased. Before

2010, borewells were 18–30 m deep. However, currently, borewells yield water only at 180–250 m depth. Natural surface water bodies have also disappeared, affecting small ruminant keepers the most, as they now must invest in buying water for livestock. Both these findings can be corroborated by data from the Central Ground Water Board (2019), as the region has moved from semi-critical to critical status in 2013–2017, indicating the overuse of groundwater. Similarly, the LULC study also indicates that water bodies have been reduced by 79% in the region (Table 3).

3.2 Impact of transitions on caste groups

In continuation to the above section, we further analyze the impact of transitions on different caste groups in the study region, particularly to gain insight into differences in land and herd size between castes and watersheds. Figures 2 and 3 present the land and herd sizes of the different caste groups. We found a significant interaction between watersheds and caste groups, which is explained by the differences observed between watersheds for the ST caste group. We found that the FC communities had the highest land size per HH (2.6 ha) in both watersheds, whereas SC communities in both watersheds had the smallest land sizes (average of 1.0 ha/HH). The ST and BC communities had higher land sizes in WS-1 than in WS-2. Similar was the case with herd size, where the FC communities had the highest herd size per HH, except for the STs in WS-1 (average of 2.3 TLUs/HH), followed by the rest. These results align with the information from the FGDs discussed above, wherein land and herd sizes generally still followed the caste hierarchy. However, a change in ownership patterns for large ruminants is observed, in contrast to the past, where lower castes also own dairy cattle. with livestock rearing had increased since the year 2000. This was attributed to the increased participation of women in government-initiated self-help groups in their villages. According to them, participation in self-help groups helped women gain access to new technologies and own livestock. However, they also reported an increased workload regarding farming and responsibility in terms of loan repayments.

3.3 Impact of transitions on women

According to the women participants, who attended all FGDs, improvements regarding access to livestock, livestock ownership, and decision-making associated with livestock rearing had increased. This was attributed to the increased participation of women in government-initiated self-help groups in their villages. According to them, participation in self-help groups helped women to gain access to new technologies and own livestock. However, they also reported an increased workload regarding farming and responsibility in terms of loan repayments.

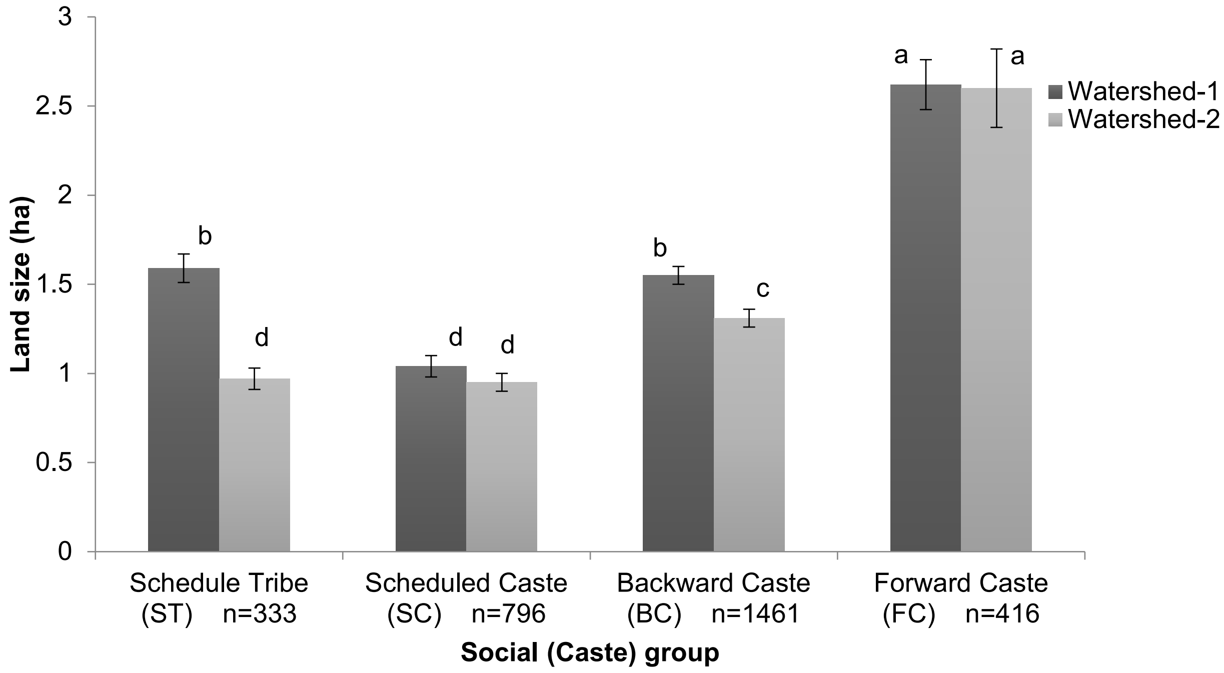

Figure 2: Land size (in ha) across caste groups (Scheduled tribe, ST; Scheduled caste, SC; Backward caste, BC; and Forward caste, FC) in both watersheds. Source: HHs survey, 2015

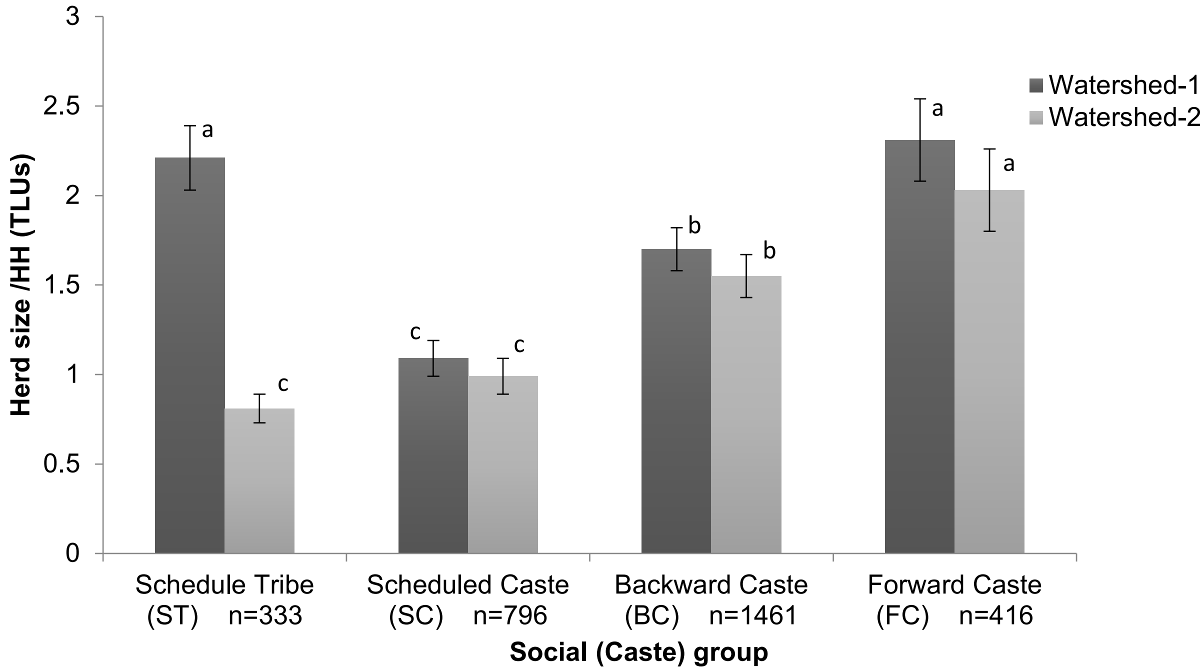

Figure 3: Herd size (in TLUs, Tropical Livestock Units) across caste groups (Scheduled tribe, ST; Scheduled caste, SC; Backward caste, BC; and Forward caste, FC) in both watersheds. Source: HHs survey, 2015

Concerning the increase in workload, women expressed that rearing improved cattle in stallfed systems demanded more time, e.g. for feeding, cleaning sheds, and animal health care, when compared to rearing cattle in grazing-based systems. Similar sensitivities were shared by women regarding changes in crop production.

For instance, the shift from rainfed food crops to irrigated cash and vegetable crops increased the workload as it involved several tasks including multiple harvests to packing - as it is carried out exclusively by women. Regarding the rearing of small livestock, women shared that the rearing of goats and poultry by them has particularly decreased compared to the past. According to them, reduced access to grazing lands and tree cover in the region due to land use changes (Table 3) meant longer grazing hours and hence avoided by older women and women with young children. Meanwhile, the reduction in native poultry rearing was due to developments in settlement areas and closer proximity of houses within the settlement areas, which led to reduced scavenging areas for chickens and conflicts among HHs.

4. Discussion

4.1 Characteristics of transition

Our study aimed at describing transitions in farming systems at a regional scale and analyzing their impacts on livestock rearing and smallholder livelihoods, along with insights on caste groups and women. The findings from the FGDs, HH survey data, LULC data (Table 3), and statistical tests (Figs. 2 & 3) all indicated that trends of how the transitions in farming systems occurred in both watersheds were similar. They were completely in the direction of market orientation and happened in a relatively short period. Matthei and Smith (2008) and Butler et al., (2014) show that such transitions are possible despite the diversity of social groups within a region. Here, community aspirations to improve living standards tend to overcome the social and cultural identities bringing in flexibility to adapt to changing circumstances.

Farming systems before 1997 were mostly subsistence-oriented, with mixed crop-livestock production and livestock having diverse functions (Ali, 2007; Kumar and Singh 2008). Between 1997 and 2015, the subsistence farming system disappeared, and specialized and market-oriented production systems emerged. The multiple roles of livestock in mixed farming systems got reduced to the role of food production mainly. In these new systems, the investments, cost of production, and input use have become relatively high, e.g. inputs for cultivating cash crops, leasing land for grazing livestock or growing fodder, leasing, or drilling borewells for water, farm mechanization, purchase of feed, and animal health- care (Singh et al., 2014; Gathorne-Hardy, 2016; Ghosh et al., 2017; Kuchimanchi et al., 2021c). Further, these changes do not seem to be limited to the study region as similar trends in changes in agricultural landscapes, livestock holdings, and cropping patterns are reported in Telangana (Reddy et al., 2016) and across India (Government of India 1997, 2002, 2007, 2012; Amjath-Babu and Kaechele, 2015; Behera et al., 2016). Such a relatively fast and region-wide transition from subsistence farming to market-oriented farming has also been reported in Africa, Latin America, and Asia by Reardon et al., (2019).

4.2 Drivers of transition

The transitions in farming systems from 1997 to 2015 in the two watersheds were driven by technological interventions, development programs promoting green and white revolution technologies with integrated approaches, and increased market demand for cash crops and certain livestock products (Behera et al., 2016; Gathorne-Hardy, 2016). An important technological intervention that triggered the transition process is village electrification, which prompted the use of motor pumps for extracting water from borewells, thereby facilitating water-intensive crop and livestock production (Tian et al., 2014). Further, we find that the sudden increase in water availability in dryland regions, due to the development programs with integrated approaches, e.g. watershed development, seemed to be a lucrative incentive for smallholders to adopt new technologies and diversify faster (van Ginkel et al., 2013) facilitating rapid transitions in farming systems.

The major market for the study region is Hyderabad, one of the biggest cities in India, growing from 3.6 million inhabitants in 2001 to 11.5 million in 2018. While the population growth in itself was an important reason for the increased demand, the income growth of the urban population also adds to this by influencing changes in food consumption patterns (Oosting et al., 2014; Kumar et al., 2017; Van der Lee et al., 2018; Reardon et al., 2019). Hyderabad has the highest food consumption expenditure per month in Telangana, of which the highest share comprises animal products (32% of the total) (Kumar et al., 2017), indicating a huge and possibly growing demand in this sector.

While FGDs identified several drivers that triggered the transitions, this is not an exhaustive list. Other drivers might have also played an important role, such as the influence of external policy situation, input of remittances, or differences in education and knowledge gains between castes or gender (Thompson et al., 2007; Reardon et al., 2019). The contribution of these other aspects to farming systems transitions needs further study.

4.3 Impacts of the transitions in farming systems on smallholder livelihoods

While transitions in farming systems across India and the study watersheds might be beneficial in some ways, not all is positive (George, 1986, 2014; Pingali, 2012; Hinz et al., 2020). Programs with integrated approaches e.g. WDPs make development dynamic and involve trade-offs as well (van Ginkel et al., 2013). For example, the transitions in the study region favored the expansion of croplands, increased use of green revolution technologies, and more focus on milk production. It also reduced the production of other livestock products, reduced diversity within farming systems, and eroded animal genetic diversity. This is a trend generally reported in the literature in transitions from subsistence to market-oriented farming systems (Puskur et al., 2004; Jayne et al., 2014; van Ginkel et al., 2013; Oosting et al., 2014; Gathorne-Hardy 2016).

Further, increased production by some farmers in the study area has triggered regional changes in water, land, and labor scarcity for others, making it compulsory for all to intensify production. The transition, therefore, was not a free process but a compulsory adaptation, inclusive of social and cultural differences due to changing circumstances (Matthei and Smith, 2008). This can be inferred because the HHs without agricultural activities or with the traditional subsistence mixed farming system together is around 10% in both watersheds. This implies that once the transition process gained momentum, farmers could either join in or step out from agriculture and is in line with Dorward et al., (2009) and Reardon et al., (2019). An additional marginalization was also witnessed in our study watersheds: we observed that only a limited fraction (38%) of HHs could maintain both crop and dairy cattle, while half of the HHs (48%) did not rear livestock owing to inadequate water resources, which is already a problem in dryland regions. This dramatic change further implies that the majority of the HHs are susceptible to risk due to the lack of diversification at the HH level, particularly the absence of livestock. The lack of crop-livestock integration may also have negative implications on agricultural production and revenue in the long term (Kuchimanchi et al., 2022c). Increasing water scarcity in the region as reported by the respondents is also in line with Sishodia et al., (2016) and the Central Ground Water Board's report (2017), which indicates a decrease in groundwater levels both within the study region and across the state.

Despite the considerable increase in cropland area, land size per HH has likely reduced over time due to fragmentation of land, e.g. by the division of property among siblings, as both settlement area and HH population (Government of India 2001, 2011) in the watersheds show an increase by 12.2% and 16%, respectively. This trend seems to be across the state; the agricultural statistics report of Telangana (2016) shows that the average landholding in the state in 2010–11 was 1.12 ha against the all-India average of 1.16 ha. Hence, it is likely that many HHs in the study region have become marginalized during the transition process and have migrated, changed their occupations, or become wage laborers.

4.4 Effect on caste groups and women

Many of the approaches of the green and white revolutions are still being out -scaled through development policies and programs as a means of poverty alleviation, e.g. integrated WDPs, self-help group movements, or agricultural subsidies and schemes.

In this context, the transitions in the two watersheds showed that lower caste groups now own improved cattle (Figs. 2 and 3) and have consequently moved up the livestock ladder (Udo et al., 2011). We also found some exceptions where the STs in WS-1 had both land and herd sizes as high as those of the FCs. These changes among lower caste groups can be attributed to several government-sponsored schemes (Reddy et al., 2016) which are specifically designed for their upliftment (Government of India, 2008). Nevertheless, our study shows that FCs continue to own the largest land sizes and cattle herd sizes, as in the past.

The transition towards intensification and market orientation was women-inclusive, as women had increased access to technologies, information, and livestock resources. However, a perceived increase in workload for women was reported in our study which is in line with other studies in India (Vepa 2005; van Ginkel et al., 2013; Pattnaik et al., 2017). In this case, this was in the form of the shift from grazing-based livestock rearing to stallfed market-oriented systems (Kohler-Rollefson, 2012) and from rainfed food crops to irrigated cash and vegetable crops. This perception of increased workload existed as certain activities in crop-livestock production is predominantly done by women, along with the already existing traditional roles within the home (Lastarria-Cornhiel and Bank, 2008). Furthermore, a general reduction in small livestock rearing and poultry rearing by women is seen, depriving them of potential activities to gain financial and nutritional security (Conroy et al., 2005; Chatterjee and Rajkumar, 2015).

5. Conclusions

Studying transitions in farming systems at a regional level highlighted various interactions in the study region, i.e. between diverse farming systems, between farming system development and natural resource use, and between regional transition and different social groups. We demonstrate how these elements impacted the development trajectory of a region with a dual effect of both enhanced incomes and marginalization of some farming HHs therein. We found that the regional transitions in farming systems have occurred in a short period, and subsistence mixed farming systems have almost completely transformed into market-orientated specialized systems in the region. Further, the function of livestock in farming changed from a multi-purpose role in the past to a market-oriented food production role. The major drivers of the transitions were found to be technological interventions, development programs with integrated approaches, and market demand for certain agricultural produce. While the transitions led to increased production by some HHs, it also led to the scarcity of water, land, and labor for others. The transition, therefore, was not a free process but a compulsory adaptation, inclusive of social and cultural differences among the HHs in the region. The HHs had to either intensify production to adapt to the transforming prospects or get marginalized. The implications of these transitions were progressive in the case of lower caste groups, as they have moved up the livestock ladder and gained assets. However, in the case of women, it was perceived unfavorable in terms of increased workloads and reduced food and financial security. Our study, thus, provides deeper insights into how transitions impact multiple aspects of smallholder livelihoods. Finding from this study could contribute to the strengthening of rural development policies to reduce risks in agricultural production, e.g. water scarcity stemming from already operational programs.

Chapter 3

Understanding farming systems and their economic performance in Telangana, India: Not all that glitters is gold

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Abstract

Farming systems are transitioning from a subsistence orientation to market orientation in response to changing food demands, technologies, and policies. In India's dryland regions, watershed development, among several other initiatives, has been a critical driver of these transitions, but their outcomes are poorly understood. The present paper investigates the characteristics and economic performance of current farming systems in a region in Telangana, India, that has undergone a rapid transition from subsistence orientation to market orientation. We surveyed 3006 farms, followed by a farm-economics study involving 75 households belonging to the three major farming systems. The gross margin was low for all systems but most inadequate for the crop-without-livestock system, highest for the crop-with-small-ruminants system, and intermediate for the crop-with-dairy system. Economic risks and natural-resource scarcity threaten the sustainability of current farming systems, and the reassessment of watershed development policies is recommended.

1. Introduction

Globally, farming systems are transitioning from subsistence-orientation to intensive or specialized market-oriented systems in response to several factors, including increasing food demands, availability of technology and inputs for production, and development policies (Tarawali et al., 2011; Udo et al., 2011; Reardon et al., 2019). While transitions towards intensification and specialization in agriculture have increased food output and income for some households (HHs), concerns about environmental and socio-economic sustainability are growing (Lebacq et al., 2013; Clay et al., 2019). Transitions in farming systems have been particularly rapid in Asia and Africa (Alexandratos and Bruinsma, 2012; Masters et al., 2013; Reardon, 2015; Reardon et al., 2019). These continents are predominantly dryland regions and are paradigmatic examples, where transitions occur in agro-climatically and biophysically challenging environments, where diverse farming systems and practices are present, and where inadequate rural infrastructure and support services exist (UNITED NATIONS, 2011; IPCC, 2019).

India clearly represents such a situation, where the dryland areas cover 69% of the geographic area and support 40% of the nation's population (Ahmad et al., 2011), and where farming systems have been subjected to transitions for over two decades (Government of India, 2012; Puskur et al., 2004; Tian et al., 2014; Amjath-Babu and Kaechele, 2015; Government of India, 2020; Kuchimanchi et al., 2021a). A range of development initiatives to support small-holder agriculture exist in India. Of those, the watershed development program (WDP) has been the most employed strategy since the 1990s and has focused on socio-economic development through modernizing agricultural production in India's drylands (Rao, 2000; Kerr, 2002; Government of India, 2008; Wani et al., 2008a, 2008b). The annual investments in WDPs were approximately 4 billion USD between 2009 and 2012 (Reddy and Syme, 2015; Government of India, 2021), indicating the program's magnitude. Currently, it is amalgamated into a larger program[1] under the ministry of land resources with a similar scale of funding. WDPs encourage the promotion of intensive production systems (e.g. use of hybrid seeds, crossbred and exotic livestock, inorganic inputs, farm mechanization, and irrigation infrastructure), which are perceived as ideal for developing countries (Chand et al., 2015; Groot and Van't Hooft, 2016). WDPs, therefore, have been identified as key drivers triggering rapid transitions in farming systems (Batchelor et al., 2003; Puskur et al., 2004; Sharma et al., 2005; Bouma and Scott, 2006; van Ginkel et al., 2013).

[1] Watershed Development Component of Pradhan Mantri Krishi Sinchayee Yojana (WDC-PMKSY); https://dolr.gov.in/en/programme-schemes/pmksy/water shed-development-component-pradhan-mantri-krishi-sinchai-yojana-wdc-pmksy.

A recent study (conducted by the authors, see Kuchimanchi et al., 2021a) mapped the transitions in agriculture and farming systems in a region in Telangana (India). It also analyzed the effect of transitions in farming systems on smallholder livelihoods in the last 20 years. The study region was subject to various development programs, of which WDPs were the predominant one[2]. That study, in line with other literature (see, e.g. Ali, 2007; Kumar and Singh, 2008a; Herrero et al., 2013; Gathorne-Hardy, 2016), indicate that farming systems before 1997 were primarily subsistence-oriented, with mixed crop-livestock production and where livestock had diverse functions (e.g. supporting agriculture, providing transportation, food, fuel, manure, and a banking asset). However, the subsistence farming system dwindled between 1997 and 2015, and specialized and market-oriented production systems emerged. The role of livestock became limited to the food production function. This was also accompanied by a significant change in land use, where croplands increased by 45% at the expense of wastelands that decreased by 75%. Increased regional production with land-use change led to groundwater scarcity in the region (Batchelor et al., 2003; Shiferaw et al., 2008; Calder et al., 2008; van Ginkel et al., 2013; Thomas and Duraisamy, 2018; Duraisamy et al., 2018). In the end, the study also reported that some HH broke the socio-economic and cultural barriers to climb the "livestock ladder" (Sones and Dijkman, 2008; Udo et al., 2011) to engage in, e.g. dairy farming. However, other HHs became marginalized and/or dropped out of the agricultural sector.

A plethora of articles have been published in the early 2000s on the agricultural and economic benefits of WDPs (Joshi et al., 2008; Wani et al., 2008a, 2008b; Palanisami and Suresh Kumar, 2009). Later articles indicated sub-optimal program outcomes due to various social, technical, and institutional issues (Bouma and Scott, 2006; Shiferaw et al., 2008; Calder et al., 2008; van Ginkel et al., 2013; Bharucha et al., 2014; Reddy and Syme, 2015). However, there is little information about the characteristics of the emergent farming systems and their economic and/or environmental performance. As indicated by Kuchimanchi et al. (2021a), the fact that rapid transitions have occurred in the area, that more intensive forms of agriculture with altered crop-livestock interactions have led to higher input use, production costs, and investments (Singh et al., 2014; Gathorne-Hardy, 2016; Ghosh et al., 2017); or that development usually entail multiple trade-offs and undesired effects (van Ginkel et al., 2013), calls for further research.

Therefore, the aim of this study is to gain insight into the characteristics of emerging farming systems and their economic performance in a dryland region of Telangana, India, that has undergone rapid transitions in farming systems. This

[2] https://iwmp.telangana.gov.in/WebReports/Content/Programmes.html

knowledge will help enhance the customization of WDPs and other development programs and ensure that their impact is sustainable.

2. Materials and Methods

2.1 Study location

The two study watersheds are in the *Rangareddy* and *Nagarkurnool* districts of Telangana, India (Figure 1). For this research, we considered the administrative boundaries of the villages falling within the watershed, given that the secondary data are aligned with administrative boundaries. The first watershed (WS-1) covers four villages inhabited by 1820 HHs, and the second (WS-2) covers three villages inhabited by 1186 HHs. The HHs in the region are primarily agrarian (91.7%), and 8.5% are engaged in non-agricultural activities due to higher education or acquiring non-farm skill sets. The predominant land category in the study region is cropland (Household survey, 2015 (this study and Kuchimanchi et al., 2021a; Government Census Data, 2011). The study region falls within the Deccan Plateau (Telangana) and Eastern Ghat agro-ecological sub-region (AESR) 7.2. The area is characterized by deep loamy and clayey mixed red and black soils, with medium to very high available water capacity and a growing season duration of 120–150 days. The climate is characterized by hot,

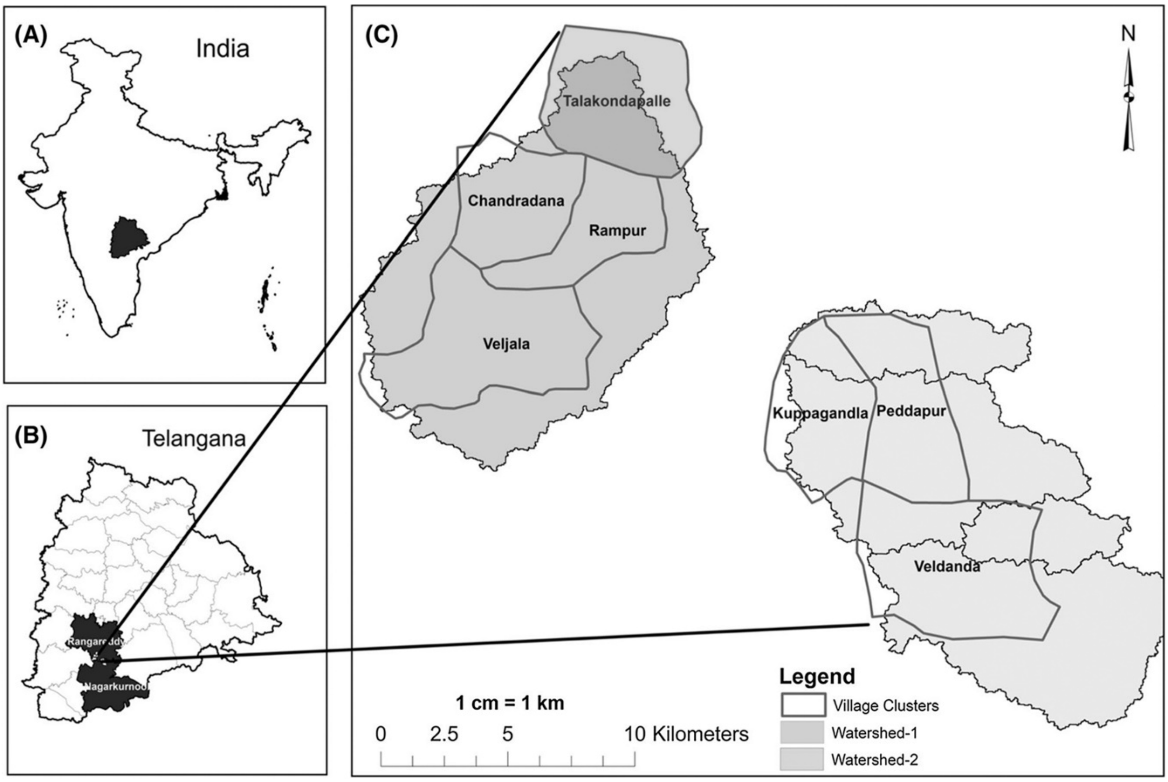

Figure 1: Location map of the study region in India
(A) Location of the state of Telangana in India. (B) The study region is within the state of Telangana. (C) The two watersheds within which the villages are distributed and the study village Talakondapalle (highlighted in gray). Source: ISRO BHUVAN portal (htpps://bhuvan.nrsc.gov.in/bhuvan_links.php, accessed 2016)

moist summers and mild, dry winters, with an aridity index (AI) of 0.2 ≤AI <0.5 (Rao et al., 2019). It is therefore classified as a semi-arid region. These districts are drought-prone, with an annual rainfall of 500–700 mm (Gajbhiye and Mandal, 1983).

2.2 Data collection and analysis

We collected data in a stepwise approach to characterize the farming systems existing within the study region. The first step consisted of conducting a HH survey in both study watersheds in 2015 (n =3006 HHs, i.e. 46% of the total HHs). It involved face-to-face interviews with household heads using a structured questionnaire. The data collected in the survey provided an overview of the population: types of livestock reared and herd sizes; farm sizes and categories of farming HHs (i.e. large farmers: >4 ha; medium farmers: 2–4 ha; small farmers: 1–2 ha; and marginal farmers: up to 1 ha); and caste groups present in the region. The caste system in India is a social hierarchical classification of communities based on occupation, which has evolved since ancient times. Based on the government classification, we considered the four main groups: forward castes (FC), backward castes (BC), scheduled castes (SC), and scheduled tribes (ST). Of the 3006 HHs surveyed, 241 (8% of the sample) had no cropland or reared livestock, and they were excluded from the study.

In the second step, we used the data from the household survey to classify the HHs according to the farming system. Our classification method was adapted from studies by Ser´e and Steinfeld (1996), Kruska et al. (2003), Notenbaert et al. (2009), Robinson et al. (2011), and Alvarez et al. (2018). The classification was based on two variables: (a) ownership of cropland and (b) dominant livestock species reared. We identified the following farming systems: crop without livestock (CWL), crop with dairy (CD), landless with livestock (LWL), crop with small ruminants (CSR), and crop with diverse livestock (CWDL), as described further in the Results section.

We conducted five focus group discussions, in the third step, one for each farming system. The participating HHs were randomly selected from the survey list (n =2765). These discussions were intended to gather information on various qualitative characteristics of each farming system. Within each farming-system category, 30 HHs were randomly selected, and 1–2 members of each household were invited to participate. The gender composition of the focus groups was mixed, with participation varying from 25 to 30 people per group. Measures were taken to ensure proper representation from all farm-size categories and social groups mentioned above. If the representation of one of these categories was lacking, we substituted a randomly selected household from the over-represented group with one from the under-represented group.

Each focus group discussion lasted 2–3 hours and was conducted in the native language (*Telugu*). To ensure that the objective of the discussions would be met, a detailed list of questions was used to guide the discussions. The key questions involved characteristics of current farming systems, including cropping and livestock-holding practices, farm infrastructure and use, off-farm jobs, access to fodder and water resources, livestock markets, and animal healthcare. The presence of different groups in each focus group discussion allowed to contrast potential divergent views between groups 'in situ'. However, and to avoid domination by the wealthy, elderly, or socially forward groups, and to ensure that sufficient time was allocated for documenting information, each focus group discussion was moderated by an experienced facilitator. All discussions were documented on charts to maintain transparency and enhance interaction with participants. We ultimately combined the quantitative data from the household survey with qualitative data from the five focus-group discussions to characterize the different farming systems (Table 1 in the Results section).

In the final step, we collected data on the economic performance of various farming systems in the study region. Although five farming systems were identified and characterized, we limited economic data collection to the three systems with consistent income from agriculture (CWL, CD, and CSR; n =2554), based on the information derived from the focus-group discussions. The HHs to be surveyed were selected according to a two-stage sampling process. In the first stage, we selected the village in each watershed with the highest presence of all farming systems. From the selected village i.e. Thalakondapalle, 75 HHs (i.e. 25 HHs per farming system) were randomly selected from the complete household list. The selection for the survey was finalized only after HHs expressed their willingness to participate. Those declining to participate were replaced by new HHs until a sample of 25 HHs per farming system was reached. We compared the distribution of castes and farm size among selected HHs to ensure that they were representative of the total regional population. Data on the economic performance of the 75 HHs were monitored once every fortnight from August 2015 to August 2016 across all agricultural seasons in India: monsoon season (July–September), winter (October–March), and summer (March–June). Each household was provided with a data-collection booklet to record data, which data collectors cross-checked at regular intervals. The following parameters were assessed, based on a structured form supplemented with related qualitative information:

(i) Farm and household characteristics: farm size, herd size, caste, type of family (nuclear or joint), level of education, sources of income, status of loans (taken and repaid).

(ii) Land use and crop production: types of crops grown per agricultural season, area under each crop, types of crops produced, the quantity of crop produce sold, input costs per crop, hired labor costs, rented farm machinery costs, and the sale price of produce sold.

(iii) Livestock production: total milk or small ruminants sold, sale prices of milk and small ruminants, cost of animal healthcare, types, quantities of feed (both purchased and grown), and cost of leasing land and hired labor.

2.3 Calculations and statistical analyses

Herd size was expressed in tropical livestock units (TLU). The conversion factors were cattle (0.7 TLU), buffalo (1.5 TLU), sheep/goats (0.1 TLU), and poultry (0.01 TLU). Labor was analyzed according to family type (i.e. nuclear or joint), assuming two working units for nuclear families and five working units for joint families. For the caste grouping prevalent in India, we considered the four main groups: FC, BC, SC, and ST, based on the Indian government classification.

We estimated total revenue, costs of production, and gross margins (GMs) at the household level as follows. The total revenue earned by a household was calculated based on the total quantity of different crop and livestock products sold multiplied by the market price, as obtained from the survey. The total costs of production were calculated based the total input costs for crop or livestock production, hired labor, and rented farm machinery costs, but excluding capital costs. The total GM was obtained by subtracting total costs of production from total revenue. All economic calculations were performed in Indian rupees (INR) and then converted to US dollars (USD) at an exchange rate of 71 INR.

The statistical analysis was to determine differences among farming systems and to gain insight into factors determining economic performance of those systems. The statistical analyses were performed using the statistical program GenStat (GenStat Committee, 2000), with a significance level of 0.05. To explore whether land use or herd size of HHs would differ across the farming system and/or between watersheds, we performed some preliminary statistical analysis (involving a GLM; see Supplementary Material). That analysis showed relevant differences across farming systems only, but not between watersheds. Hence, we performed an ANOVA with a post hoc Tukey test to identify differences in terms of land use and herd size across farming systems.

To explore the economic performance of the three farming systems and gain insight into the factors contributing to it, we undertook a two- step approach: ANOVA with post hoc Tukey test to identify differences in economic performance (i.e. GM) across farming systems, and a general linear model (GLM) for each farming system to identify factors contributing to the GM. In the GLM model, the dependent variable was GM, with the independent variables of herd size, farm size, caste, and family type (as a proxy for labor), along with all two-way interactions. Caste, labor, and their two-way interactions were not significant in any of the farming systems, and they were therefore removed from the model. Given the skewed distribution indicated by the

GLM, we followed the approach described by Kuchimanchi et al. (2021a) for the statistical analyses, converting the values into their natural logarithms. To ensure that values of 0 would also be transformed, we added one unit to all values. Once the tests were run, the mean values and confidence intervals were then back-transformed (Johnson et al., 1994) and one unit was subtracted from each value.

3. Results

3.1 Types of farming systems found in the region

Data from the household survey and five focus-group discussions revealed the presence of five types of farming systems in the region, as described below (also see Table 1). Native poultry was kept for subsistence food needs across all farming systems, and it was therefore considered part of all systems.

3.1.1 Crop without livestock (CWL)

This system accounted for the highest proportion of HHs (48%). Most of these HHs were either marginal (40%) or small farmers (37%), with medium farmers constituting 21% and large farmers constituting only 2%. The HHs in this system owned very few borewells, which were seasonally functional. Cropping was thus predominantly rain-fed, with limited irrigated crop production. Low water availability limited crop farming in this system to one agricultural season per year. Monocropping of cash crops (e.g. maize and cotton) was predominant. Farmers reported that cropping practices were intensive and required higher investments, as they grew mainly cash crops, rented farm machinery, and used hybrid seeds and inorganic fertilizers. They added that cash crops were preferred to food crops, given their higher market value. These HHs mainly sold the produce, and the crop residues were either burnt or tilled back into the soil. Participants in the focus groups added that increased drought conditions over the years had led to failed crops, reduced yields, and increasing debts. These HHs owned no livestock due to diminishing common property resources for grazing, less family labor, or limited capacity to hire labor or invest in leasing lands for grazing or borewells. The limited availability of water resources further inhibited them from taking up dairy production. A lack of livestock resulted in greater use of inorganic inputs in crop farming, as livestock manure was unaffordable. Many HHs, therefore, opted to take off-farm jobs in order to earn income, although they noted that such jobs were not adequately available. Most of the HHs also depended on the public food-distribution system to meet their food needs, as they cultivated mainly cash crops.

3.1.2 Crop with dairy (CD)

The second most prevalent category was the CD system (38% of all HHs). Most of the HHs in this system were medium (42%) and small farmers (31%), with marginal

Table 1: General farming-system characteristics, as derived from the household survey and focus group discussions

Types of farming systems	Crop without livestock (CWL)	Crop with dairy (CD)	Landless with livestock (LWL)	Crop with small ruminants (CSR)	Crop with diverse livestock (CWDL)
	n = 1326	n = 1063	n = 188	n = 165	n = 23
Ownership of land	Y	Y	X	Y	Y
Ownership of livestock	X	Y	Y	Y	Y
Distribution per farm type					
Marginal (>1 ha)	40%	15%		20%	21%
Small (1–2 ha)	37%	31%		32%	26%
Medium (2–4 ha)	21%	42%		32%	48%
Large (>4 ha)	2%	12%		30%	4%
Cropping characteristics	Rain-fed, Limited irrigation, Monocropping	Irrigated, Continuous irrigation, Mixed cropping		Rain-fed; Limited irrigation, Monocropping	Rain-fed, Mixed cropping
Crops	Predominantly cash crops	Cash & food crops with residues, green fodder		Predominantly cash crops	Predominantly food crops
Livestock characteristics (dominant species)	Native poultry	Large ruminants crossbred/exotic cattle/buffalo	Native poultry and small ruminants	Small ruminants	Diverse livestock species
Crop - livestock practices	Intensive specialized technologies	Intensive specialized technologies	Traditional, subsistence	Intensive specialized technologies	Traditional, subsistence
			Depend on CPRs for grazing	Depend on CPRs for grazing	Depend on CPRs for grazing
Farm infrastructure	Traditional/basic	Use farm machinery	Traditional/Basic	Use farm machinery	Traditional/basic

Source: Household survey and focus-group discussions, 2015; CPR – common property resources farmers constituting 15% and large farmers constituting 12%. The HHs in this system grew cash crops in combination with food crops and perennial green fodder. Participating farmers reported choosing cash crops that provided additional crop residues for livestock (e.g. maize, groundnuts, rice, or vegetables), depending on the availability of water for irrigation. These HHs also practiced intensive crop farming, with drip and sprinkler systems for irrigation, farm machinery, and better housing for livestock. They also owned multiple borewells that were functional throughout the year and invested heavily in groundwater extraction. In this system, dairy farming was market-oriented, using predominantly crossbred or exotic dairy cattle (Jersey or Holstein breeds). Farmers mentioned having many opportunities to engage in and develop dairy farming through government schemes, subsidies, and bank initiatives. They added that despite the high production investments required for dairy farming, the consistent and reliable income that it provided led them to continue. In addition, they noted that exotic breeds required particularly high production costs, due to their greater susceptibility to diseases and the need for high-quality feed and more water resources. The farmers also reported managing scarce water resources by limiting crop production to one season and by diverting the water for dairying. According to them, dairy farming was far more reliable than crop farming, and it was therefore sought by many farmers. In general, HHs in the CD system did not engage in off-farm work for additional income.

3.1.3 Landless with livestock (LWL)

The third most prevalent category was the LL system (6.8% of all HHs). In this system, the primary source of income was from agricultural wage work or off-farm jobs. Agricultural activities that primarily involved rearing livestock was need-based, and the number of livestock raised depended on anticipated income needs. The livestock reared consisted mainly of native poultry (97%) or goats (5%). Farmers considered goat rearing as challenging, due to a lack of common property resources in the villages and the inability to lease shrublands for grazing goats. According to the respondents, native poultry rearing has decreased, due to limited scavenging area and the increased incidence of conflicts among HHs because of infrastructural developments within the settlement areas.

3.1.4 Crop with small ruminants (CSR)

The fourth most prevalent category was the CSR system (6.0% of all HHs). The majority of HHs in this system comprised medium (32%) and small farmers (32%), followed by marginal (20%) and large farmers (13%). These HHs cultivated both rain-fed and irrigated crops, which provided suitable residues for livestock. The CSR system was the only system that cropped for two agricultural seasons per year. Crop-management practices were intensive, but predominantly using livestock manure.

Like the CWL farmers, these HHs also owned few borewells, which were functional mostly in the monsoon. They also owned only basic farm implements, but they were able to rent farm machinery if needed. In contrast to the HHs in the CD system, these housed leased borewells instead of deepening or digging new ones. In this system, both sheep and goats were reared, but sheep rearing was dominant. HHs rearing sheep were part of the traditional livestock- keeping community of Telangana state (known as *Gollas*) and belonged to the BC caste group. Although goats were reared irrespective of caste, they were mostly reared by impoverished HHs belonging to the SC and ST caste groups. The herd sizes for sheep averaged 125 sheep per household. As noted by focus-group participants, the costs of sheep rearing have increased, given the need to rent private lands and borewells for grazing and water resources. They added that flock sizes were determined by resource availability, which caused annual variability, as competition for land resources for grazing in the region was increasing. Farmers resorted to migration only during severe drought conditions. Goat rearing was a largely seasonal activity, and it was more predominant in the summer or taken up based on the income needs of individual HHs. Herd sizes ranged from 10 to 55 goats per household, depending on whether goat rearing was a primary or supplementary source of income. Focus-group participants stated that goats were grazed mainly on lands with tree and shrub cover. Large goat flocks would require large tracts of grazing land (according to farmers, about 25–30 ha for a flock of 55–60 goats). The scarcity of such land has therefore reduced goat keeping. Sheep-rearing HHs rarely depended on off-farm labor, whereas those rearing goats frequently depended on off-farm labor or agricultural wage work. HHs also depended on markets or the public food- distribution system to meet their food needs, although dependence was greater for goat-rearing HHs.

3.1.5 Crop with diverse livestock (CWDL)

The least prevalent category was the CWDL system (0.8% of all HHs). Most HHs in this category were medium farmers (48%), followed by small (26%) and marginal farmers (21%). Only 4% were large farmers. Crop production in this system veered towards food crops, using seasonally available water resources, and limited external inputs. In this case, livestock keeping was integrated and intended to support crop production. According to the participants in the focus groups, this had been the most prevalent system in the 1990s. Diverse livestock species (predominantly local breeds of cattle, buffaloes, goats, and poultry) were reared in this system. Crop and livestock products were consumed predominantly at home, and only surplus production, if available, was sold. The primary source of income for these HHs consisted of remittances from family members working in cities.

Land and herd sizes are presented in Table 2. Land and herd sizes differed

Table 2: Comparison of land (in ha) and herd sizes (in TLUs) across farming systems

Farming system	n	Land size	Herd size
Crop without livestock (CWL)	1326	1.2 (0.0) [b]	0.03 (0.0) [d]
Crop with dairy (CD)	1063	2.1 (0.1) [a]	3.21 (0.1) [b]
Landless with livestock (LWL)	188	0.0 (0.0) [c]	0.25 (0.9) [d]
Crop with small ruminants (CSR)	165	1.9 (0.1) [a]	4.74 (0.5) [a]
Crop with diverse livestock system (CWDL)	23	1.7 (0.2) [ab]	1.85 (0.2) [c]

Note: Different superscripts within a column (land size or herd size) indicate significant differences ($p < 0.05$); Source: Household survey, 2015

across systems. HHs in the CSR system had the highest herd size in comparison to all systems. The CD, CSR, and CWDL systems had comparable land sizes. The LWL system was not comparable to any system in both land and herd sizes

3.2 Economic performance of farming-systems

In this section, we present the results of the economic-performance study of only the CWL, CD, and CSR systems (92% of the sample), as they provided consistent income from agriculture. The revenue, costs of production, and total GM per household are displayed in Table 3 for all three systems under study. For HHs in the CD and CSR systems, GM comprised income from crop and livestock production. For those in the CWL system, it consisted of crop production and off-farm activities. The economic performance of crop production is explained by the various crop management and input requirements across systems. As indicated in the focus-group discussions, the CWL and CD systems limited crop production to the monsoon agricultural season each year, while the CSR system managed crop production for both monsoon and winter seasons each year. In terms of inputs, the CWL system incurred the highest crop- production costs, followed by the CSR system and then the CD system. The differences were due to the types of crops grown, with cash crops having higher costs, associated inputs, and the availability of livestock manure, which replaced expenses for inorganic inputs.

Detailed information about the production costs for livestock rearing is presented in Table 4. The costs for dairy farming were substantially higher than those for small ruminants. The high production costs in dairy farming were attributed to feed purchased from external markets (accounting for 88% of the total production costs per annum). The CD system also exhibited the greatest variation in the GM. Some of the HHs in this system had negative GMs in the summer due to low milk production combined with high feed requirements by the cattle. The CSR system was the most

Table 3: Economic performance (in USD) of three farming systems (i.e. CWL, CD, and CSR) in the study region

Income sources	Agricultural seasons[1]	Revenue[2]	Cost of production[3]	Total Gross Margin
Crop without livestock (CWL)				
Crop	Monsoon	309.7 (286.5)	224.4 (197.7)	87.4 (96.6)
	Winter	-	-	-
	Summer	-	-	-
Off-farm livelihood	Monsoon	56.9 (36.6)	-	56.9 (36.6)
	Winter	51.7 (34.9)	-	51.7 (34.9)
	Summer	107.0 (52.4)	-	107.0 (52.4)
Total		**525.2 (359.2)**	**224.4 (197.7)**	**303 (210.4)**
Crop with dairy (CD)				
Crop	Monsoon	1171.8 (2208.3)	138.9 (222.3)	1032.8 (1994.1)
	Winter	-	-	-
	Summer	-	-	-
Livestock	Monsoon	1324.1 (1037.8)	1174.3 (163.4)	149.7 (260.0)
	Winter	2176.0 (1892.8)	1059.3 (925.6)	1116.6 (1461.3)
	Summer	889.6 (788.7)	1570.0 (1659.2)	-680.4 (1270.9)
Total		**5561.4 (5927.6)**	**3924.7 (3870.6)**	**1618.7 (4992.2)**
Crop with small ruminants (CSR)				
Crop	Monsoon	1012.9 (1383.4)	194.0 (216.8)	818.8 (1313.0)
	Winter	441.4 (557.7)	210.9 (235.0)	444.9 (495.1)
	Summer	-	-	-
Livestock	Monsoon	245.9 (449.1)	298.9 (170.2)	-53.1 (443.5)
	Winter	1255.5 (1770.8)	176.7 (127.9)	1078.7 (1772.2)
	Summer	1567.9 (1422.9)	154.4 (77.3)	1413.2 (1382.3)
Total		**4738.1 (5720.5)**	**1040.8 (736.9)**	**3538.2 (5302.0)**

Note: Figures in USD; conversion factor used: INR 71; SD: standard deviation values in brackets.
Source: Household-level longitudinal study 2015–2016.
[1]Monsoon agricultural season (July–September); winter agricultural season (October–March); summer agricultural season (March–June)
[2]Sale price of milk 0.36 USD/kg & Sale price of meat 3.5 USD/kg at farmgate.
[3]Cost of production of crops includes costs of land preparation (rent of machinery/bullocks), hired labor, and input; the cost of production for livestock includes costs of animal healthcare, leasing lands for grazing, purchased fodder, hired labor, and fodder production in owned land.

profitable farming system, due to low feed costs (as compared to dairy production) and high market price for meat (3.5 USD/kg). The highest costs per annum in the CSR system were for animal health care and for leasing grazing lands. These factors

Table 4: Production costs (in USD) for livestock rearing in crop with dairy (CD) and crop with small ruminant systems (CSR)

Farming system	Agricultural seasons[3]			
Crop with dairy (CD)	**Monsoon**	**Winter**	**Summer**	**Total**
Production details[1]				
Animals in milk (#/HH)	5.0 (3.0)	4.0 (3.1)	4.0 (3.1)	4.3 (3.1)
Average milk prod. (l/HH)	3550.4 (2875.7)	5942.2 (5168.6)	2429.3 (2154.7)	2153.7 (3973.9)
Costs (USD/HH/y)				
Healthcare[2]	75.0 (59.2)	57.2 (50.3)	48.6 (53.1)	180.9 (117.7)
Feed and fodder (purchased)	1050.2 (967.1)	1478.3 (1664.1)	945.6 (877.2)	3474.0 (3297.7)
Fodder production (own)	28.1 (31.4)	73.4 (48.5)	57.1 (30.1)	179.0 (99.6)
Other: leasing land for grazing	78.2 (85.3)	-	-	84.4 (109.3)
Total	**1234.0 (1143.1)**	**1608.9 (1762.8)**	**1051.3 (960.3)**	**3914.9 (3624.3)**
Crop with small ruminants (CSR)	**Monsoon**	**Winter**	**Summer**	**Total**
Production details[1]				
Average flock size (#/HH)	87.2 (61.1)	88.2 (62.9)	74.1 (45.7)	83.2 (55.1)
Average animals sold (#/HH)	19.5 (12.2)	32.5 (23.8)	25.9 (26.2)	25.9 (20.7)
Costs (USD/HH/y)				
Healthcare[2]	120.2 (72.8)	179.5 (133.9)	131.6 (69.9)	143.8 (31.4)
Feed and fodder (purchased)	-	36.7 (19.0)	40.9 (28.1)	77.6 (51.6)
Fodder production(own)	-	-	-	0.0
Other: leasing land for grazing	219.0 (134.1)	-	-	219.0 (134.1)
Total	**339.4 (206.9)**	**216.2 (152.9)**	**172.5 (99.0)**	**440.4 (217.1)**

Note: Figures in USD; conversion factor used: INR 71; standard deviation values in brackets. Source: Household-level longitudinal study 2015–2016

[1]Units: USD/HH/y.

[2]Includes veterinarian fees, medicines, and other treatment-related costs.

[3]Monsoon agricultural season (July–September); winter agricultural season (October–March); summer agricultural season (March–June)

nevertheless did not seem to impair economic performance. The CSR system managed to obtain a high GM in the summer, the most unproductive season in dryland regions due to high temperatures and water shortages.

Another factor addressed in the survey was loan access and repayment. The findings revealed that HHs took loans from multiple sources to continue farming. Among the three systems, CD HHs had the most loans from cooperative banks (80%), local pawnbrokers (64%), and self-help groups (40%) simultaneously. The loan values were also higher in comparison to those of HHs in the other two systems. In the CWL system, HHs accessed government crop loans (84%), self-help group loans (60%), and government schemes (16%) to manage crop production. In contrast, only 50% of CSR HHs took loans, and only from cooperative banks. Focus group discussions indicated that loans from self-help groups were entirely availed by women, however, loans from banks were from both genders, as women also had access to banks. Despite formal credit sources, informal credit sources (pawnbrokers) are still being accessed particularly by the CD HHs. This situation can be related to the high investment and production costs in dairying farming, where formal credit options work due to pending loan repayment.

The GM of the HHs in the CSR system was statistically higher than that of those obtained by HHs in the CD and CWL systems ($p < 0.05$). There were no statistical differences between the CD and CSR groups ($p > 0.05$). The linear regression analysis revealed that factors explaining the GM were dependent on the farming system. First, caste and family type (as a proxy for labor availability) were not significant in any of the farming systems. For the CWL system, land size was the only statistically significant variable ($p < 0.001$) clarifying the GM. For the CSR system, both herd size ($p < 0.001$) and land size ($p < 0.05$) were significantly and positively correlated with GM. For the CD system, however, none of these variables was statistically significant ($p > 0.05$). In Figure 2 below, we further illustrate the relationship between herd size and

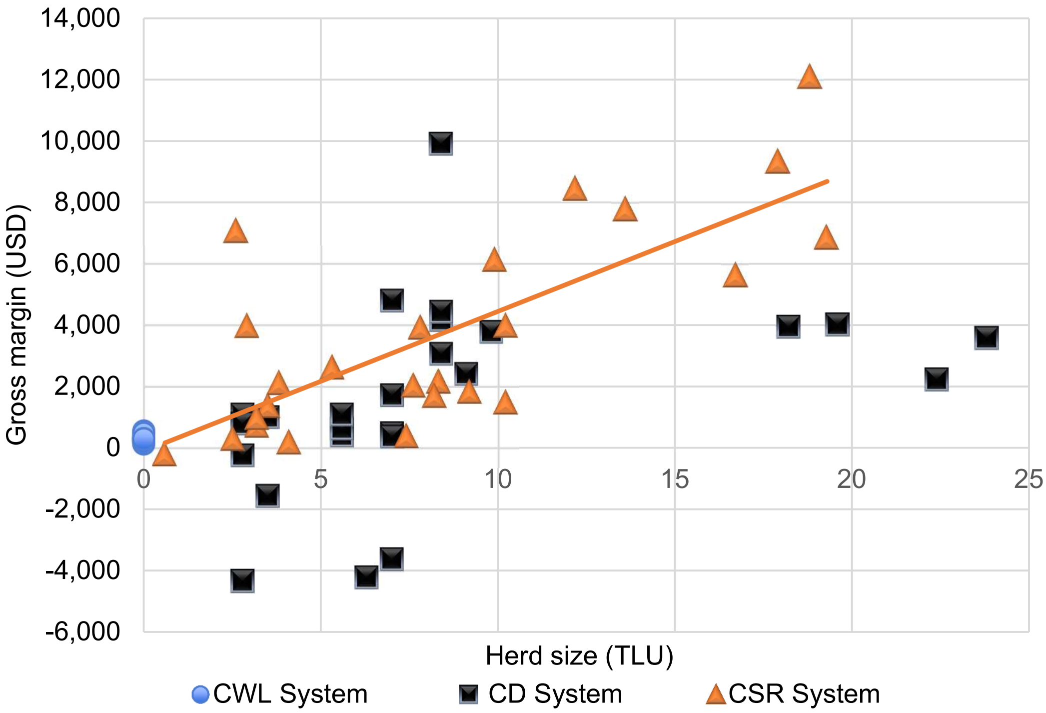

Figure 2: The relationship between herd size (in TLUs) and gross margins (in USD) for the three farming systems under study

Note: Only the regression line for the CSR system is plotted because it was the only farming system in which herd size resulted in a significant factor for gross margin. Note: crop without livestock (CWL), crop with dairy (CD), and crop with small ruminant (CSR) farming systems. Source: Economic performance study of three farming systems (2016–2017, n =75)

GM, which helps to explain why herd size is an explanatory variable for the CSR system, but not for the CD system. For the CSR system, GM increased along with herd size, as indicated by the significant regression line. In contrast, the CD system exhibited high variation, as CD farms with low herd size obtained both negative and positive GMs, while those with large herd sizes obtained only moderate to low GMs. The CWL system had the lowest gains and no livestock.

4. Discussion

The characterization of farming systems in the study region revealed that the CWL, CD, and CSR systems were variants of intensive, specialized, and market-oriented farming systems, while the LWL and CWDL were variants of subsistence farming systems. The majority of the HHs in the region (86%) fell into two farm categories: CWL and CD. The CSR system, although lucrative, was dominated by the BC communities (the *Gollas*) in the region, given that sheep, rearing has been their traditional occupation for generations. For LWL and CWDL systems, livestock rearing was a need-based livelihood activity, and it usually involved poultry and seasonal goat rearing. Although the CWDL system was the most prevalent in the past, the majority of HHs have now transitioned away from this system (Kuchimanchi et al., 2021a).

Further analysis of the three systems revealed that the CWL system is a medium-input/low-output system, the CD system is a high-input/high-output system, and the CSR system is a medium-input/medium-output system. In terms of economic performance, the CSR system showed the best performance, as explained by the low water requirements and low feed production costs (e.g. leasing croplands and use of existing CPRs). The profitability of this system was further enhanced by growing market demand and the current market price for small ruminant meat. The system also adapted to the dynamic context by adjusting herd sizes to the decreasing availability of common property resources (Kuchimanchi et al., 2021a). All these factors make the CSR system suited to the dryland context. Despite having the highest revenues, the CD system was less profitable, due to high production costs. This system exhibited high variability in GMs from moderate to substantially negative records across HHs (Fig. 2). This variability might have been due to the influence of other factors not included in this study (e.g. knowledge of dairy management, management practices, embeddedness in supply chains for feed supply or milk collection, or access to credit schemes and subsidies) (Oosting et al., 2014; Van Der Lee et al., 2018). In addition, the consistent income obtained from dairy farming came at the expense of crop production in the winter season, as scarce water resources were diverted for dairying. This strategy resulted in the loss of additional income for CD HHs, in contrast to those in the CSR system, which cultivated crops for two seasons each year, in addition to rearing small ruminants (see Table 3). These findings thus suggest that engaging in dairy production may not be a resilient option for HHs in semi-arid regions (Chand et al., 2015; Ghosh et al., 2017; Clay et al., 2019). The CWL system consistently exhibited low economic performance, with low revenues attributable primarily to higher production costs for cash crops and market volatility (Thapa, 2009; Kumar, 2014).

In line with other studies such as, Sallu et al. (2010); Ten Napel et al. (2011); Ayeb-Karlsson et al. (2016); Kuchimanchi et al. (2021b) we find that the trend of intensification and specialization in farming, particularly in the CWL and CD systems, has increased generic risks and decreased flexibility for coping with disturbances and shocks. For example, the CWL system (the most dominant system) reflected the absence of crop diversity and livestock and was dependent on off-farm employment, which was not regularly available. The lack of crop- livestock integration at the farm level increases dependence on inorganic fertilizers (Kuchimanchi et al., 2021b), which reduces soil-carbon levels, subsequently affecting soil fertility, crop productivity, and revenue in the long term (Herrero et al., 2010; Thornton and Herrero, 2015). These factors make HHs in this system more reliant on external inputs and market conditions to continue farming, leading to higher risks in the long term.

The CD system (the second most prevalent system) was the most desired by HHs in the region, as it provided consistent income throughout the year (Kuchimanchi et al., 2021a, 2021b). However, this system had compromised GMs and can be seen as entailing high risk, as dairy farming is heavily dependent on external markets for feed resources, scarce water resources and milk collection. Small landholdings limit feed production and increase the amount of external feed that HHs are forced to purchase to guarantee production. Further, as reported in studies by Sishodia et al. (2016) and the Central Ground Water Board (2017, 2019), the region is currently experiencing high water scarcity, and the situation is likely to worsen. In addition to being risky, therefore, the CD system may be economically unviable in dryland regions (Ghosh et al., 2017; Clay et al., 2019), contrary to general perceptions. For this reason, the promotion of dairy farming among poor HHs should be a point of concern for development programs, especially in dryland regions. In the farming systems examined, higher revenues were associated with higher costs due to increased use of purchased inputs, credit, and animal healthcare services (Udo et al., 2011). If these costs cannot be limited, they offset revenues, hinder profits, and perpetuate the ‘poverty trap’ (Tittonell and Giller, 2013). In this study, this situation is illustrated by the fact that HHs in the CWL and CD systems had high levels of credit and debt, due to insufficient income and low profits (Tables 3 & 4). Increasing credit and debt thus pose a risk, as they are likely to become intertwined with farming strategies aimed at simply adopting a system and continuing to farm. Over time, this situation often leads to a range of social-ecological consequences (e.g. marginalization, inequality, low adaptive capacity, high infrastructure investments, and regional water scarcity), all of which perpetuate vulnerability to climate change (Taylor, 2013; Ramprasad, 2019; Kuchimanchi et al., 2021a,b).

Lastly, WDPs tend to promote specific farming systems (i.e. dairy farming), that has induced changes in land use, cropping patterns, and livestock rearing in terms of herd size, animal type, and purpose (Puskur et al., 2004; Sharma et al., 2005). While these changes have a positive effect on the ability of lower caste groups to attain resources and engage in dairy farming (this study; Reddy et al., 2016; Kuchimanchi et al., 2021a), it also shows that 48% of the HHs participating in this study had no livestock, and 6.8% kept livestock only temporarily in contrast to the past (Kuchimanchi et al., 2021a). This also suggests that those who cannot afford intensive livestock production tend to reduce their livestock rearing or to rear small ruminants as needed, thus indicating marginalization (see Tables 3 and 4 on current expenditure & Kuchimanchi et al., 2021a). In view of the above, it is necessary to re-assess current approaches in ongoing WDPs as intensification and specialization, do not necessarily result in higher economic performance, especially in biophysically constrained environments such as dryland areas (in line with various scholars e.g. Benoit et al., 2009; Ryschawy et al., 2012; and Ripoll- Bosch et al., 2014). Our reason for emphasizing the biophysical aspect is that, despite the better standards of socio-economic and infrastructural conditions in Telangana (Indian National Human development report, 2018), the lower economic performance in farming is still observed and across all farming systems (this study, Kuchimanchi et al., 2021a,b). We, therefore, suggest considering alternative development strategies for HHs, such as “area-wide integration”, feed self-sufficiency, or farm diversification to trigger better economic results or enhance the viability of farms in the long term (Oosting et al., 2014; Thornton and Herrero, 2015; Van Der Lee et al., 2018), particularly in environmentally constrained regions (Udo et al., 2011; Ripoll-Bosch et al., 2014). Further, to manage the dynamics of intensification and specialization in farming systems (Jayne et al., 2014; Amjath-Babu and Kaechele, 2015; Thornton and Herrero, 2015), the institutional capacity-building at the village level in WPDs should be strengthened with new information and approaches. This is well demonstrated by some civil society organizations, using community engagement approaches and tools[3]. Such approaches, combined with science-based evaluations of ongoing programs, could

[3] http://www.fao.org/climate-smart-agriculture-sourcebook/enabling-frameworks/module-c1-capacity-development/c1-case-studies/case-study-c111-the-andhra-pradesh-farmer-managed-groundwater-systems-apfamgs-project/en/
http://fes.org.in/source-book/groundwater-game-practitioners-manual.pdf
https://wotr-website-publications.s3.ap-south-1.amazonaws.com/156_Making_the_Invisible_Visible_A_Manual_for_Preparing_the_CoDriVE_Visual_Integrator.pdf

help avoid the implementation of conflictive technological development (Nedumaran et al., 2014) and create knowledge about complex social-ecological processes. This approach could also facilitate an interactive learning space and promote local innovations by tapping local or traditional knowledge systems to improve the management of dryland environments (Tamou et al., 2018).

In all, we urge the need for interdisciplinary research (particularly in dryland ecosystems) to assess the relative feasibility of varied farming systems in dryland conditions, the socio-economic impact of agricultural intensification in dryland ecosystems e.g. indebtedness and access to credit, HH dietary diversity or gender implications. Also, we encourage the implementation of mechanisms that can facilitate continuous research on farming systems development and their economic and environmental performance. This will help to better anticipate farming systems trajectories and the potential (undesired) effects of development strategies, also those within the WDP operational framework.

5. Conclusion

The current study investigates the characteristics and economic performance of the farming systems that emerged in the last decades in the dryland region of Telangana, India. The characterization studies revealed the presence of five distinct farming systems, based on agricultural activity and tenure of livestock type. These farming systems were crop without livestock (CWL), crop with dairy (CD), landless with livestock (LWL), crop with small ruminants (CSR), and crop with diverse livestock (CWDL). The farming systems represented variants of specialized, intensive, and market-oriented farming (i.e the CWL, CD, and CSR systems), and variants of subsistence farming (LWL and CWDL systems). The majority of the HHs in the region that had consistent income from agriculture fell into the three intensive types of farming systems, i.e. CWL, CD, and CSR. The economic performance study of these three systems revealed that intensive, specialized, and market- oriented farming did not always result in high economic results. This was evident in the case of the two dominant systems (CWL and CD), which showed low and highly variable performances. Moreover, these two systems were subject to various types of risks and lacked the flexibility needed to cope with disturbances and shocks. Despite exhibiting the best economic performance and being the most suitable system for dryland regions, the CSR system is likely to be constrained by dwindling grazing resources in the future. Our results suggest that intensive and specialized farming systems may impair the potential of development strategies, such as WDP, aimed at environmental conservation and may pose a risk for HHs regarding their ability to cope with disturbances in the long term. These outcomes are the opposite of what WDPs seek to achieve. We infer that an inadequate understanding of the effects of current farming systems and how they manifest over time has generated these unintended consequences. Therefore, we recommend that the current approaches of the WDPs should be overhauled by better understanding and further continuous research on the characteristics of current farming systems, their impacts in socio-economic and environmental terms, and the anticipation of their future development trajectories. Likewise, further research should address the potential (undesired) effects of development strategies, such as impacts on natural resources and on HH livelihoods, including role of financial mechanisms or effects on dietary variety. Further research and monitoring, and the changes in development mechanisms, shall pave the way forward for the implementation of sustainable development programs in rapidly changing socio-ecological systems.

Supplementary Material

In this supplementary material, we present an additional statistical analysis of the two watersheds under study where we compared the variables land size and different farming systems.

Material and Methods

Land size and herd size are widely used variables to characterize smallholder HHs and have a large influence on-farm productivity and economic performance (Rahman et al., 2007; Oosting et al., 2014; Ripoll-Bosch et al., 2014). Hence, to understand whether the land size and herd size were affected by the watershed or farming system type we used a general linear model (GLM) on the general sample of HH (n= 2554).

The statistical analysis was performed using the statistical program GenStat (GenStat Committee, 2000). We used a significance level of 0.05. The GLM model consisted of the dependent variables land or herd size per HH, the independent variables were watershed and farming system (i.e. crop without livestock (CWL), crop with dairy (CD), landless with livestock (LWL), crop with small ruminants (CSR) and crop with diverse livestock (CWDL), and the interaction watershed × farming systems. Pairwise post hoc comparisons between treatment means were performed using Fisher's least significant difference method.

The dependent variables in the GML analysis showed a skewed distribution. To perform the statistical analysis, we followed the same approach as in Kuchimanchi et al., (2021a). We first converted the values into their natural logarithm and to ensure the transformation of values of 0 into natural logarithm, we added one unit to all values. Once the tests were run, the mean values and confidence intervals were then back-transformed (Johnson et al., 1994) and subtracted by one unit.

Results

We analyzed whether the land size and herd size of HHs were affected by the farming systems identified or the watershed. Figures 1 and 2 present the land and herd sizes of the different farming system typologies in the study watersheds. The statistical analysis revealed a significant interaction between farming systems and watersheds for the herd and land size. The interaction is only explained by the slightly different behaviors of specific farming systems per watershed. For instance, WS-1 usually showed larger land and herd sizes per HH across farming systems, but not always: as no differences in land size between watersheds were observed for the LWL system and largely for CWDL, or in herd size for the CWL, LWL and CWDL systems. In terms of land use the CSR, CD, and CWDL systems had the largest land size, especially in WS1. HHs in the CWL system had the smallest land size/HH in both watersheds.

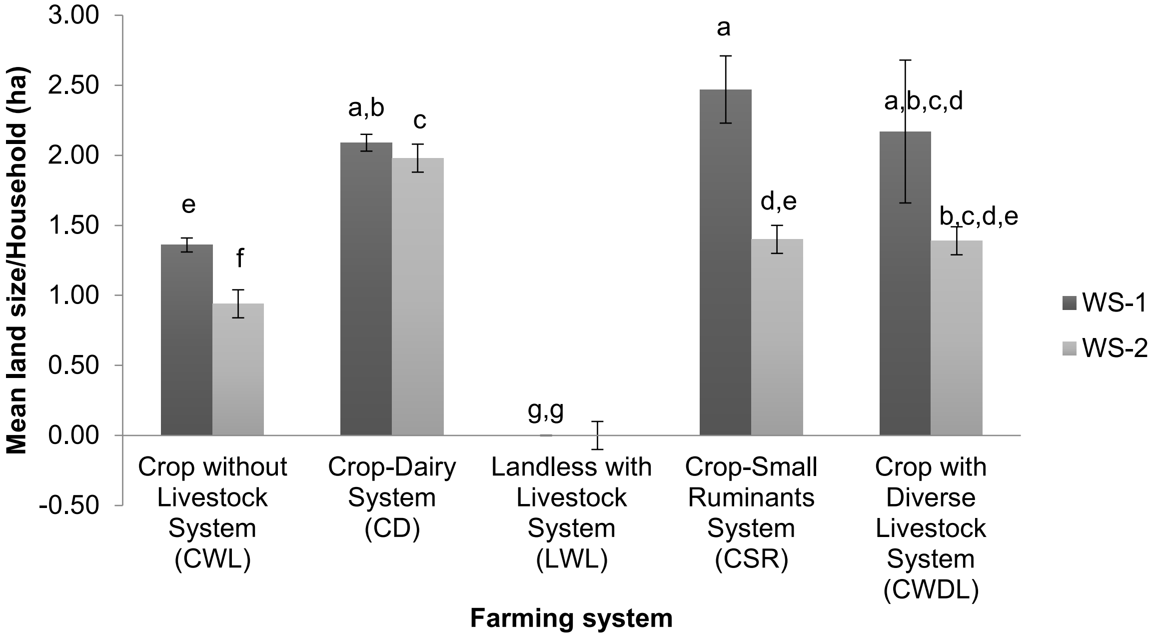

Figure 1: Land size per household per watershed and farming system typology

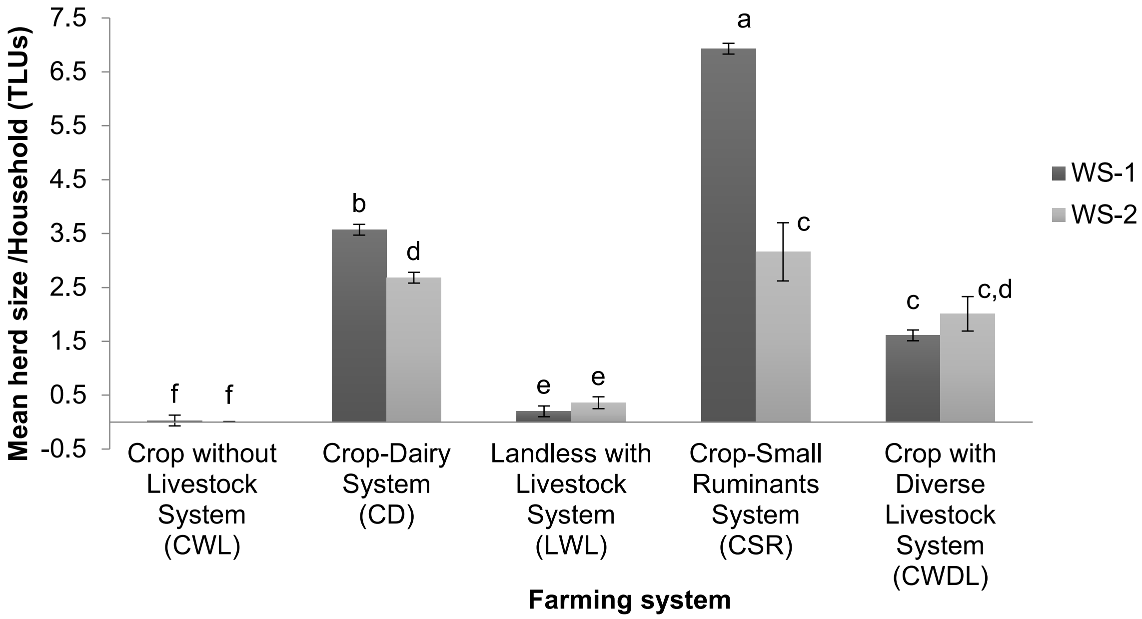

Figure 2: Herd size per household per watershed and farming system typology

Note for both figures: The statistical differences are on logarithmical scale, while numbers represented are not. Source: HH survey, 2015

Chapter 4

The impact of intensive farming systems on groundwater resource availability in dryland environments: a watershed level study from Telangana, India

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Abstract

Intensification of agriculture in India has increased food self-sufficiency. However, it has also led to unwanted environmental impacts, particularly the increased pressure on groundwater resources. These impacts are most severe in the dryland regions of the country. Therefore this paper aims to understand the impact of intensified forms of agriculture on the availability of water resources in a dryland watershed in Telangana, India. To achieve this, we first assessed the water use of three main farming systems in the study region. We then calculated the water balance at the watershed level to understand the agricultural impact on groundwater availability within the watershed. The three farming systems studied were the crop without livestock system (CWL; 48% of households), the crop-dairy system (CD; 38% of households), and the crop with small ruminants system (CSR; 6% of households). The results indicated that the CD system used the highest quantity of water (8122 m^3/household/y), followed by the CSR (2869 m^3/household/y) and CWL (1833 m^3/household/y). CWL and CD systems comprise 86% of the households, making these systems the largest water users. Finally, the water balance of the whole watershed showed a deficit of – 0.8 Mm^3/y. Cultivation of water-demanding non-dryland crops, increased specialization of farming systems, and management practices in current farming systems are the factors causing over-utilization of water and subsequent groundwater depletion. We also realize that the current policy environment and other drivers such as decreasing landholdings and market forces also induce increased water use in production. We, therefore, conclude that there is a need to promote agro-ecologically suitable farming strategies, improve the existing technological options and introduce new policies that reduce the over-use of water resources for sustainable agricultural production in dryland regions.

1. Introduction

Transitions in farming systems are occurring rapidly worldwide due to increasing population, income growth, urbanization, and development policies (Reardon et al., 2019). Such transitions are also happening in India, where extensive traditional mixed farming systems are transitioning towards intensive farming systems (Amjath-Babu and Kaechele, 2015; Kuchimanchi et al., 2021a). These intensive farming systems are characterized by high use of inputs such as land and water, specialize in crop or livestock production as the primary income source, and are market-oriented (Udo et al., 2011; Oosting et al., 2014; Kuchimanchi et al., 2021b). While intensification of agriculture in India has increased food self-sufficiency, it has also led to rapid changes in agricultural land use and affected water availability and water use. Landscape changes have led to high precipitation runoff, low groundwater infiltration, and increased groundwater use for irrigation, particularly in dryland environments (Thomas and Duraisamy, 2019; Duraisamy et al., 2019; Jain et al., 2021).

India is the world's largest groundwater user (Jain et al., 2021; Paria et al., 2021), using around 230 km^3 of groundwater per year (World Bank, 2012). According to Rosegrant et al., (2009), about 65% of that groundwater is used to produce half of the country's food. However, the prospects of climate change indicate a negative impact on the future availability of water resources and a threat to India's food security (Kumar and Kumar, 2013; IPCC, 2014). Sixty percent of India is classified as dryland, i.e. arid and semi-arid (UNCCD, 2010), where water is already scarce. The continued growth of intensive agricultural production in these regions (Kuchimanchi et al., 2021 a,b), coupled with growing water demand from population growth and industrial sectors, is likely to result in severe water scarcity in India in the near future (Kumar and Kumar, 2013).

The impact of agricultural production on the use of water resources in India has been studied from a range of perspectives and using different methods, such as crop-livestock water productivity (Jayanthi et al., 2000; Singh et al., 2004; Blümmel et al., 2009; Haileslassie et al., 2011; Clement et al., 2010; Bekele et al., 2017), surplus water use in farming and growing water scarcity in dry regions (Batchelor et al.,2003; Bouma and Scott, 2006; Barucha et al., 2014), and water resource auditing and/or modeling at watershed level (Perrin et al., 2012; Ariyama et al., 2019; Singh and Saravanan, 2020). All these studies deliberate on the impact of excessive water use at a landscape or regional level or analyze crop-livestock water productivity, water use, and water availability at a watershed level in isolation. Hence, to our knowledge, there are no studies that look at coupled interactions between water use by different farming systems at the farm level and its relation to the water availability at the watershed level in India.

Therefore, the current paper aims to understand the impact of water use by current dominant forms of intensified agriculture on the availability of groundwater resources in a dryland watershed in Telangana, India. To achieve this, we first assess the water use of the three main farming systems in the study region. We then calculate the water balance at the watershed level to understand the agricultural impact on groundwater available within the watershed. Gaining insight into water use by the different farming systems, their practices, and their effect on water availability could help anticipate future water scarcity and, therefore, better planning (Kuchimanchi et al., 2021a, b, 2022c). In the discussion section, we reflect on the possible social and economic implications of the current developments in farming systems on water resource availability in dryland regions.

2. Material and Methods

2.1 Background and study area

The current study was a part of a larger research project that studied the transition of farming systems, covering aspects of characterization of emergent farming systems, assessment of their economic performance, and analysis of their vulnerability to climate change (Kuchimanchi et al., 2021, a, b, 2022c). The research project was conducted in two watersheds: the *Rangareddy* and *Nagarkurnool* districts in the southern state of Telangana, India (Figure 1), covering a sample of 3006 households (HHs; 46% of the total population) in both watersheds.

The watersheds fall in a drought-prone area (Manickam et al., 2012). The annual rainfall is 500–700 mm, distributed around the South-West (June to September) and the North-East (October to November) monsoon seasons. The aridity index of the region is $0.2 \leq AI < 0.5$ (Rao et al., 2019) and is therefore classified as semi-arid. The mean maximum temperature in the area varies from 43 °C in May to the mean minimum temperature of 13 °C in December. The length of the growing period for crops ranges from 120 to 150 d/y. The watersheds are situated in the agro-ecological sub-region 7.2, characterized by deep loamy and clayey mixed red and black soils with medium to very high available water holding capacity (Gajbhiye and Mandal, 1983). These soils are classified as Group -B soils which have a minimum infiltration rate of 3.8 - 7.5 mm/h. The water transmission of such soils is identified as moderate rate, ranging from 0.15 to 0.30 mm/h (US SCS soil classification standards, SCS, 1956). The geology of the study region is dominated by crystalline basement rock (Archaean granite and Gneiss). A region with this type of geology is characterized by low porosity or sediment and has a low ability to store water, resulting in frequent failures in both installation of borewells and water withdrawal after the installation.

Farming systems in both watersheds have similar characteristics (Kuchimanchi et al., 2021a, 2022c), and therefore the current study was conducted only in watershed 1 (WS-1; Figure 1). The total geographic area of WS-1 is 9463 hectares (ha), covering four villages and a population of 1820 HHs, of which 1688 HHs (92%) were into agriculture-based livelihoods. The average farm size in the region is 1.0 ha, and the average herd size is 1.6 Tropical Livestock Units[1] (TLU) (Government Census Data, 2011; Kuchimanchi et al., 2021a).

Within WS-1, *Thalakondapalle* was chosen as the representative village for data collection (Table 1). Although five farming systems were present in the village, data collection was limited to the three farming systems obtaining consistent income from

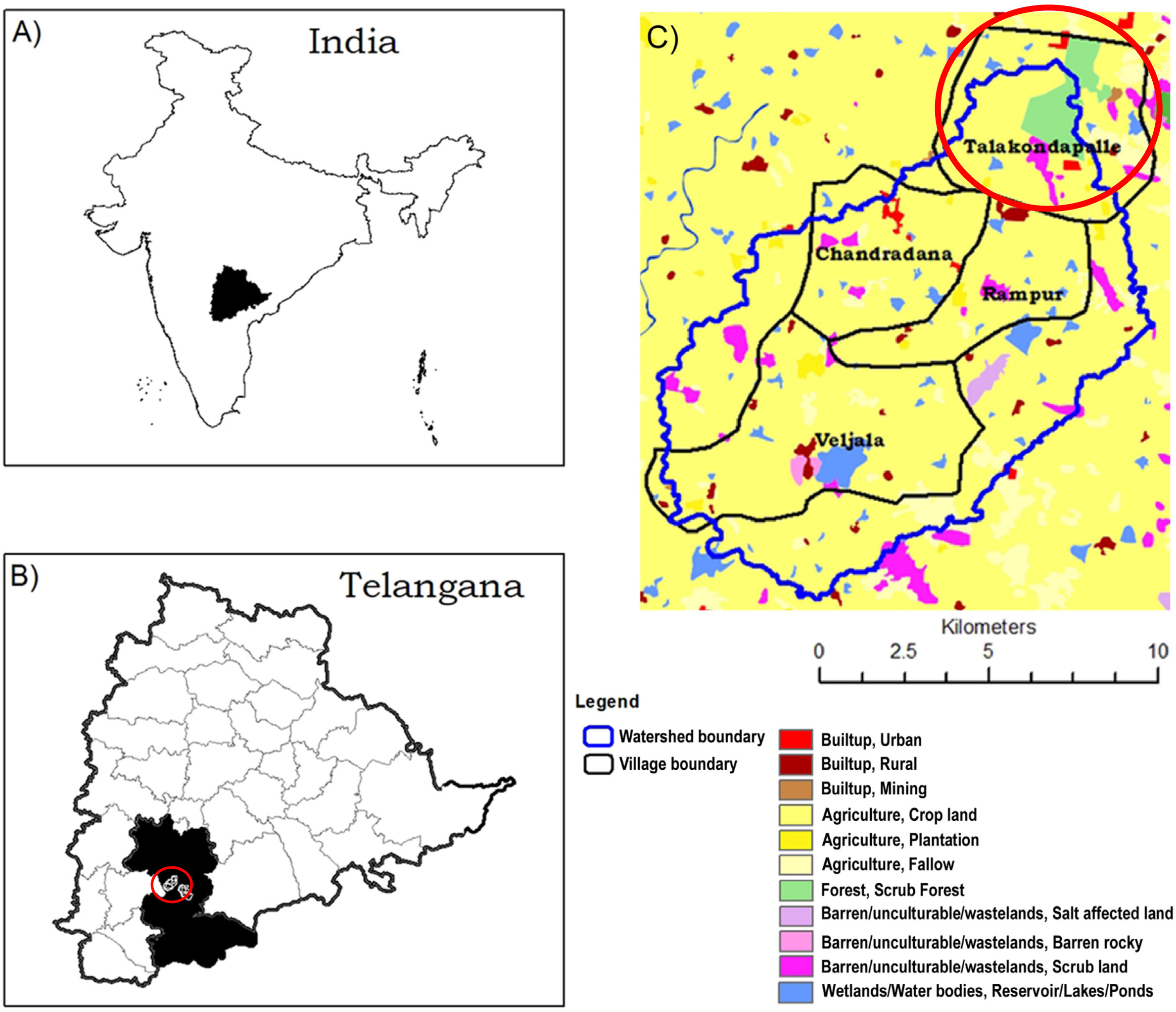

Figure 1: (A) Location map of the study region in India. (B) The study region is within the state of Telangana. (C) The study watershed and the representative village *Talakondapalle* (circled) overlayed on land use and land cover base. Source: Ortho rectified Resourcesat-2 Data from LISS-III sensor of 3 seasons pertaining to 2015-16 (Monsoon season-Kharif: Aug-Oct, Post-monsoon-Rabi: Dec-Mar, Pre-Monsoon-Zaid: Apr-May)

[1] Where 1 TLU =average live weight of 250 kg therefore 1 adult cow = 0.7 TLU, 1 adult buffalo = 1.5 TLU, sheep/goat =0.1 TLU

Table 1: Distribution of households in farming systems across four villages in WS-1

Villages	Farming systems					Total
	Crop Without Livestock	Crop with Dairy	Crop with Small Ruminants	Landless With Livestock	Crop With Diverse Livestock	
Thalakondapalle*	304	232	32	22	1	591
Chandradana	189	193	16	10	1	409
Rampur	147	102	8	85	0	342
Veljal	195	115	13	16	7	346
	835	**642**	**69**	**133**	**9**	**1688**

Source: Kuchimanchi et al. 2021a, 2022c; * is the selected village for the study

Table 2: General characteristics of the farming systems under study in WS-1

	Crop Without Livestock (CWL)	Crop with Dairy (CD)	Crop with Small Ruminants (CSR)
Farmers (n)	835	642	69
Average land size (ha)	1.3	2.1	2.4
Average herd size (TLUs)			
Large ruminants	0	3.4	0
Small ruminants	0	0	5.5
Distribution per farm size			
Marginal (<1ha)	35%	13%	16%
Small (1-2 ha)	38%	30%	19%
Medium (2.01-4 ha)	21%	45%	42%
Large (>4 ha)	6%	12%	23%
Cropping characteristics	Rain-fed, Limited irrigation, Monocropping	Irrigated, Mixed cropping	Rain-fed, Limited irrigation, Monocropping
Crops	Cotton, Maize	Rice, Pulses, Vegetables, Green fodder	Cotton, Maize, Groundnut
Dominant livestock species	Native poultry	Large ruminants: crossbred/exotic cattle/buffalo	Small ruminants
Crop - livestock practices	Intensive practices	Intensive, specialized technologies	Intensive, specialized technologies Depend on common lands for grazing
Farm infrastructure	Traditional/basic	Use farm machinery	Traditional/basic

Source: Kuchimanchi et al., 2022c

agriculture (Kuchimanchi et al., 2022c), i.e. the Crop Without Livestock (CWL), Crop with Dairy (CD), and the Crop with Small Ruminants (CSR). These systems were the most widespread and covered 92% of the HHs in the region. A brief description of the three farming systems under study is provided in Table 2 (for further information, see Kuchimanchi et al., 2022c).

2.2 Framework of analysis and data collection

In this study, a watershed is the unit of analysis. It is considered a social-ecological entity wherein the farming systems and people constitute the social component, and the watershed and its natural resources comprise the ecological component (Reddy and Syme 2015). Figure 2 shows the framework for data collection and analysis that was followed to calculate the water balance in the study watershed. In brief, we first collected data about agricultural water use at the farm level by conducting borewell pump discharge tests and a longitudinal survey for the three main farming systems in the region. Second, we collected data on domestic water use by HHs at the watershed

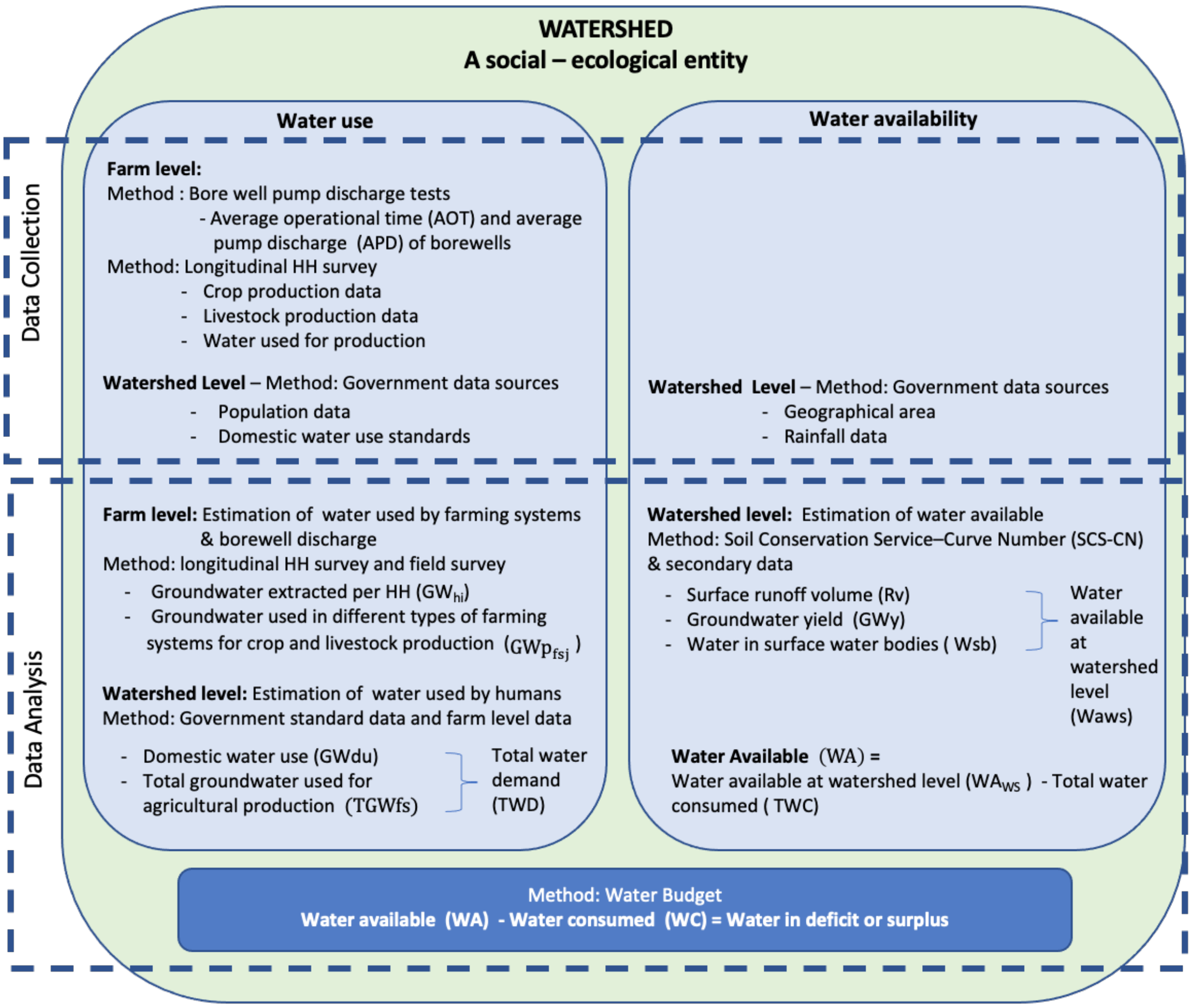

Figure 2: Framework for data collection and data analysis

level using secondary data sources. Agricultural and domestic water use together comprise of the water consumed by all HHs at the watershed level. Third, we used secondary data sources to estimate water availability at the watershed level. Finally, we calculated the water balance at the watershed level by subtracting the water consumed (WC) from the water available (WA).

2.3 Data collection of water use in different farming systems at the farm level

We estimated the water use at HH level for the different farming systems by first conducting borewell pumping tests and second by conducting a longitudinal study. As borewells were the main source of irrigation in the region, the average operation time (AOT) and average pump discharge (APD) of borewells needed to be determined. Hence the pumping tests were conducted in the summer season, using five representative borewells selected across the watershed. The selection of borewells, running the pump discharge tests, and determining the average discharge rate of borewells in the region was done with the help of a hydro-geologist and according to the standard methodologies used for groundwater monitoring studies (CGWB, 2019). Additional details about pumping test procedures can be found in Balasubramanium (2017).

For the longitudinal study, 75 HHs (i.e. 25 HHs per farming system) were randomly selected from the complete household list of the representative village *Thalakondapalle*. The HH sample for the study was finalized after the selected HHs expressed their willingness to participate. Those declining to participate were replaced by new HHs until a sample of 25 HHs per farming system was reached. We also controlled the distribution of castes and farm size among selected HHs to ensure that the sample was representative of the total regional population. If the representation of one of these groups/categories was lacking, we substituted a randomly selected HH from the overrepresented group.

After selecting the HHs, the longitudinal study was performed using a structured questionnaire between August 2015 and August 2016. The questionnaire was field-tested and amended before use. The final version for the actual data collection was then printed into booklets. Farmers were trained on how to fill the booklet with the data required. The data collection process was monitored fortnightly by data collectors and once a month by the first author of this manuscript to ensure accuracy, consistency and to assist the farmers in data collection. The data collected in the booklets were as follows:

- General HH Profile – Respondent name, farm typology (i.e. CWL, CSR, CD system), and land size
- Crop data – types of crops grown during each agricultural season, the area for each crop and green fodder (ha), the area under irrigation (ha), and crop yield (kg).

- Livestock data – type of livestock owned (cattle: indigenous, crossbred, exotic, bullocks; buffalo: indigenous and graded; sheep, goat), physiological stage of animal (i.e. young/adult, dry, heifer, in milk), herd size, total milk produced (l/d per animal) and animals sold per household (type and number).
- Water-use data: borewells owned and used (n), water storage structures used (i.e. water troughs and tubs, utensils), and their sizes (l).
- Water used for livestock production, i.e. drinking and animal management (e.g. cleaning and cooling animals) for large and small ruminants (l/d).

Groundwater from borewells was used as drinking water for animals, as surface water bodies in the region were dry. Therefore, the water consumed by animals for drinking was calculated by estimating the water capacity of the containers (e.g. troughs, plastic tubs or drums, steel utensils) used to provide water to animals in each HH. This was done by giving water to the animals by type (large or small ruminants) in different physiological stages (dry and in milk) to determine the exact water intake. This value was then multiplied by the times the animals were provided with water per day. This procedure was done daily every other week during the longitudinal study. In the case of small ruminants, in the summer season, when borewells were completely dysfunctional on their farms, shepherds leased borewells from other farmers in the region who were willing to share water resources. The same procedure given above was followed. Further, to avoid duplication, care was taken that water from storage structures, though owned by very few HHs (i.e only 12 out of 25 HHs in the crop-dairy system) was not used for drinking water. This was also reconfirmed by farmers as stored water was not provided to the animals.

2.4 Data collection of domestic water use at the watershed level

The domestic water use, including water used for cooking, bathing, sanitation needs, and washing clothes by HHs (i.e. 55 l/d/person), was derived from secondary government data sources - the government census data (2011) for population details and the National Rural Drinking Water Program (NRDWP) guidelines (2013).

2.5 Data collection of groundwater use and availability at the watershed level

The groundwater availability in the region was estimated using secondary data sources. The average rainfall data in the region was obtained from the Indian Meteorological Department database (accessed in 2018). Data regarding the total geographical area (e.g. runoff water, see section 2.6.3) and predominant land categories in the region was obtained from the government census (2011). We assumed that water stored in surface water bodies was 20% of the surface runoff in the region. This was based on ground realities found in Kuchimanchi et al. (2021 or chapter 2, see table 3 indicating a significant lower area), field visits that indicate shallow depth, and literature on potential evapotranspiration for the region (Rao et al., 2012).

2.6 Calculations

Using the data from the longitudinal study and the secondary data, we calculated the water groundwater consumption and availability in the study watershed in four steps: 2.6.1) estimating water consumed in different farming systems at the farm level, 2.6.2) estimating domestic water use at the watershed level, 2.6.3) estimating groundwater availability at the watershed level, and finally, 2.6.4) calculating the water balance at the watershed level. As the watershed covers four villages, these calculations were also done at the village levels using the same method to understand the variation in water use and groundwater available across villages .

2.6.1 Estimating water used in different farming systems at the farm level

Using the average operation time (AOT) and average pump discharge (APD) obtained from the borewell pumping tests (see section 2.3), the total groundwater extracted per HH (GW_{hi}) was determined. Here the difference in the number of active borewells owned by HHs was the main factor determining the total groundwater extracted per HH (GW_{hi}). Therefore the general equation for this is:

$$GW_{hji} = AOT_j * APD * n_{hi} \quad [1]$$

Where:

GW_{hji} = *the groundwater extracted by all active borewells per HH h in farming system j in season i (l/d)*
AOT_j = *the annual average operational time of borewells per HH in farming system j (h/d)*
APD = *the average pump discharge per borewell (l/h)*
n_{hi} = *number of active borewells owned by HH h in season i (longitudinal study)*
h = *the farms/households in farming system j*
j = *the type of farming system i.e. CWL, CD or CSR*
i = *season (monsoon -20 weeks, winter – 20 weeks, summer – 12 weeks)*

a) Estimation of water use in the different farming systems

After estimating the groundwater extracted per HH we calculated how the water extracted is used for crop and livestock production by the different farming systems under study. The equation therefore is:

$$GWp_{hji} = GWlp_{hji} + GWcp_{hji} \quad [2]$$

Where:

GWp_{hji} = *the groundwater used for agricultural production in HH h in farming system j in season i (l/d)*
$GWlp_{hji}$ = *the groundwater used in HH h for livestock production in farming system j in season i (l/d)*
$GWcp_{hji}$ = *the groundwater used for crop production in HH h in farming system j in season i (l/d)*
h = *the farms/households in farming system j*
j = *the type of farming system i.e. CWL, CD or CSR*
i = *season (monsoon -20 weeks, winter – 20 weeks, summer – 12 weeks)*

in the above equation [2] $GWlp_{hji}$ was calculated by :

$$GWlp_{hji} = ADWa_{hji} * na_{hji} + ADWy_{hji} * ny_{hji} + GWfm_{hji} \quad [2.1]$$

Where:

$GWlp_{hji}$ = *the groundwater used for livestock production in HH h in farming system j in season i (l/d)*
$ADWa_{hji}$= *the average drinking water for an adult animal in HH h in farming system j in season i (l/animal/d)*
$ADWy_{hji}$= *average drinking water for a young animal in HH h in farming system j in season i (l/animal/d)*
na_{ijh} = *the average number of adult animals in HH h in farming system j in season i (n)*
ny_{ijh} = *the average number of young animals in HH h in farming system j in season i (n)*
$GWfm_{hji}$ = *the groundwater used for farm management in HH h in farming system j in season i (l/d)*
h = *farms/households in farming system j*
j = *the type of farming system i.e. CWL, CD or CSR*
i = *season (monsoon -20 weeks, winter – 20 weeks, summer – 12 weeks)*

And $GWfm_{hji}$ per HH was calculated by:

$$GWfm_{hji} = \sum_{k=1}^{n} VWS_{khji} * NSE_{khji} \quad [2.1.1]$$

Where :

$GWfm_{hji}$ = *the groundwater used for farm management in HH h in farming system j in season i (l/d)*
VWS_{khji} = *the volume of water in storage structure k in HH h in farming system j in season i (l/d)*
NSE_{khji} = *the number of times storage structure k is emptied in HH h in farming system j in season i (n/d)*
k = *the storage structures used to store water during season i*
h = *farms/households in farming system j*
j = *the type of farming system i.e. CWL, CD or CSR*
i = *season (monsoon -20 weeks, winter – 20 weeks, summer – 12 weeks)*

$GWcp_{hji}$ per HH is calculated by :

$$GWcp_{hji} = GW_{hji} - GWlp_{hji} \quad [2.2]$$

Where:

$GWcp_{hji}$ = *the groundwater used for crop production in HH h in farming system j in season i (l/d)*
GW_{hi} = *the groundwater extracted in HH h season i (l/d) (Refer to equation [1] above)*
$GWlp_{hji}$ = *the groundwater used for livestock production in HH h in farming system j in season i (l/d)*

b) Estimation of water use for farming at the watershed level

Once the water use in different farming systems was determined, the total water used in agricultural production in all farming systems i.e TGW_{fs} was calculated at the watershed level. For the systems under study, i.e. CWL, CD, and CSR, farm-level data from the longitudinal study was used. To determine the distribution of HH in a particular farming system we used the proportions described in Kuchimanchi et al. (2022c). That study covered the same area and nearly 50% of the population, and determined that 48% of HH belonged to CWL system, 38% to CD system, 6% to CSR system. The reminding 8% belonged to Crop with diverse livestock (CWDL) and to Landless with livestock (LWL). The same farm-level data from the longitudinal study were used to quantify water use in these systems. This was possible as the CWDL had a similar cropping pattern. For livestock, the data on herd size was taken from a previously conducted HH survey done by Kuchimanchi et al. (2021a, 2022c). The average water requirements for the different livestock species were used from the current study. We considered these distributions of HH per farming system and governmental census data (2011) to extrapolate to watershed level. For HHs with non-agricultural activities, only domestic water use was accounted for. Hence, TGW_{fs} is calculated by :

$$TGW_{fs} = \sum_{j=1}^{5} GWp_{fs_j} \qquad [3]$$

And GWp_{fs_j} is:

$$GWp_{fs_j} = \sum_{i=1}^{3} GWp_{ji} * d_i * n_j \qquad [3.1]$$

Where:

TGW_{fs} = the total groundwater used in all farming systems at the watershed level (l/y)
GWp_{fs} = the groundwater used for agricultural production by all HHs of farming system j at the watershed level (l/y)
GWp_{ji} = the average groundwater used for agricultural production in a HH h in farming system j in season i (l/d)
d_i = days per season i i.e. 140 days in monsoon, 140 days in winter, and 85 days in the summer
n_j = total number of households in farming system j
h = farms/households in farming system j (source Government population census, 2011)
j = the type of farming system i.e. CWL, CD, CSR, CWDL, LWL
I = season (monsoon -20 weeks, winter – 20 weeks, summer – 12 weeks)

2.6.2 Estimating domestic water use at the watershed level

Similarly, the total water used for domestic use per year (GW_{du}) was calculated by multiplying the total population in the watershed (i.e. 15952) by 55 l/person/d according to the standard prescribed by NRDWP guidelines (2013).

2.6.3 Estimating water availability at the watershed level

The Soil Conservation Service–Curve Number (SCS-CN) method (USDA, 1956; Mishra and Singh, 2003, Singh, 2017) was used to estimate water availability within a watershed based on the rainfall received in the region. While this method was initially developed to estimate direct runoff from rainfall in particular events (e.g. storms) (USDA, 1956), posterior developments and modifications have allowed the model to be applicable to long-term hydrological simulations (e.g. seasons or years) (Mishra and Singh, 2004; Singh, 2017). We follow the approach suggested by Singh (2017). This method is based on an empirical approach to the relationship between rainfall (P) and ground conditions of the watershed (soils, management, and antecedent moisture content). The formula is provided below:

$$Q = \frac{(P-Ia)^2}{(P-Ia+S)} \qquad [4]$$

$$S = (25400/CN) - 254 \qquad [4.1]$$

Where:

Q = Runoff Depth is the runoff that directly enters the stream immediately after the rainfall, it includes surface runoff, prompt interflow, and rainfall on the surface of the stream (mm)

P = average rainfall, i.e. 687 mm for the last 5 years using daily rainfall data obtained from IMD (2018) (mm)

I_a = initial abstraction, i.e. 0.3 mm under Indian conditions (Singh, 2017) (mm)

S = maximum potential retention, i.e. 84.6 mm (US SCS soil classification standards) (mm)

CN= 75 given the soil type, land use and cover, antecedent moisture content of the watershed (US SCS soil classification standards, (Singh, 2017))

Note: As the whole of the watershed has similar land use and land cover and the major land type is agricultural lands (see figure 1 for reference), the Ia and S values were considered the same for the whole watershed

Once the runoff depth (Q) is calculated, the runoff volume (RV) and groundwater recharge[2] (GW_R) were calculated. The empirical formulas for these are:

$$RV = 1000 * H_0 * F \qquad [5]$$

Where:

RV = runoff volume is the total amount of water expected in a given period of time (in this case, season) in the catchment (in this case, a watershed) (m^3/y)

H_0 = runoff depth. In this study, as rain gauge data was not available, the value of H_0 = Q in equation [5] (mm)

F = Area (km^2)

$$GW_R = C * A * P / 10 \qquad [6]$$

Where:

GW_R = is part of the runoff that gets infiltered into the ground and reaches the groundwater storage in the soil (m^3)

C = runoff coefficient is identified as 7.5 It is an empirical value obtained based on the Ia, considering the soil type (red sand – loam soil) in the watershed which falls in Group B as (USDA-SCS soil classification , Singh, 2017)

A = area of the watershed (ha)

P = rainfall (mm)

2.6.4 Estimating the water balance at the watershed level

A water balance (WB) was then calculated using the following equation from above:

$$WB = WAws - TWC \qquad [7]$$

Where WAws :

$$WAws = GW_R + Wsb \qquad [7.1]$$

And TWC :

$$TWC = TGWfs + GWdu \qquad [7.2]$$

[2] Source: https://calculator.agriculture.vic.gov.au/fwcalc/information/determining-catchment-yield-for-planning-farm-dams

Where:

WB = *the water balance at the watershed level, i.e. water in surplus or deficit (m^3/y)*

WA_{WS} = *the water available at watershed level (groundwater + water in surface water bodies) (m^3/y)*

TWC = *total water consumed (m^3/y)*

GW_R = *Groundwater recharge (m^3) (Equation [6])*

Wsb = *water in surface water bodies (m^3) assumed to be 20% of total surface water runoff in the watershed based on evapotranspiration values of the region (Rao, et al., 2012) and ground realities (see table 3 of chapter 2)*

GWdu = *the domestic water use (m^3/y) (section 2.6.2)*

TGWfs = *the water used by all different farming systems in the region (m^3/y) is done by extrapolation using government census population data (Equation [3])*

3. Results

3.1 Estimating water use in different farming systems in the region

Pump discharge parameters differed among borewells (Table 3). The high variation in the pumping discharge was due to the low recharge capacity of the borewells. The borewells' location and depth also determine the functionality and variation. The average pump discharge value for borewells in the region was determined as 3464 l/h. This value was used as the standard to calculate the total water extracted by borewells in each HH. Though electricity in rural areas was available only for seven h/d, the study showed that the average time borewells pumped water was 3.2 h/d, amounting to extracting 12470 l/d.

The longitudinal study on water use at the farm level by the three farming systems revealed the following (Table 4):

CWL system (n=25): HHs in this system owned 0.9 (SD 0.3) borewells on average, which were functional only in the monsoon season. The average area under crops was 1.3 ha (SD 1.1 ha) per HH during the study year. The crops grown by these HHs were predominantly maize and cotton. The average water used for crop production was 1833 m^3 (SD 676 m^3) per HH.

Table 3: Results of borewell pumping tests in WS-1

Borewell	Discharge rate (l/h)	Pump power (HP)	Pumping time (h/d)	Pumping discharge (l/d)
1	2000	5	1	2000
2	2964	5	3	8892
3	3928	5	4	15711
4	5227	6	5	26133
5	3205	5	3	9614
Average	**3464**	**5.2**	**3.2**	**12470**
SD	(1202)	(0.4)	(1.5)	(9052)

Source: Borewell pump discharge testing 2016; SD in brackets.

Table 4: Farm characteristics and average (SD) water use per year of the three farming systems in the study watershed

	Monsoon (Jun-Sept)	Winter (Oct-Feb)	Summer (Mar-May)	Total
Crop Without Livestock system	N=25			
Borewells in working condition (#)	0.9 (0.3)	-	-	
Area under crops and green fodder (ha)	1.3 (1.1)	-	-	
Water for crops and fodder (m^3/y)	1833 (676)			
Total groundwater used for farm production (m^3/y)	**1833 (676)**		**-**	**1833(676)**
Crop with Small Ruminants system	N=25			
Borewells in working condition (#)	1.7 (0.7)	1.0 (1.0)	-	
Area under crops and green fodder (ha)	1.2 (1.5)	1.2 (0.5)	-	3.0 (2.0)
Water used for crops (m^3/y)	1274 (564)	1472 (685)	-	2747 (1249)
Average herd size (TLUs)	87.2 (61.1)	88.8 (62.9)	74.1 (45.7)	83.2 (56.6)
Water used for livestock (m^3/y)	35.3 (25.5)	49.2 (33.1)	37.9 (28.2)[1]	122 (86.8)
Total groundwater used for farm production (m^3/y)	**1309 (590)**	**1522 (718)**	**37.9 (28.2)**	**2869 (1336)**
Crop with Dairy system	N=25			
Borewells in working condition (#)	4.0 (2.9)	3.2 (1.8)	1.2 (1.9)	
Area under crops and green fodder (ha)	1.2 (1.2)	1.2 (0.5)	1.1 (0.5)	3.5 (2.2)
Water for crops and fodder (m^3/y)	3640 (1929)	2456 (998)	1158 (417)	7254 (3345)
Herd size (TLUs)	8.6 (5.0)	7.9 (5.3)	5.8 (5.1)	7.4 (5.1)
Animals in milk (#)	5.0 (3.0)	4.0 (3.1)	4.4 (3.1)	4.3 (3.1)
Unproductive animals[2] (#)	5.5 (3.0)	6.9 (5.1)	6.5 (5.4)	6.3 (4.5)
Drinking water for animals (m^3/y)	63.2 (47.7)	52.8 (49.8)	46.7 (35.7)[1]	163 (134)
Water used for maintenance (m^3/y)	68.7 (269)	278 (460)	361 (403)	708 (1132)
Water used for livestock (m^3/y)	132 (316)	331 (510)	408 (438)	871 (1265)
Total groundwater used for farm production (m^3/y)	**3771 (2246)**	**2792 (1505)**	**1560 (855)**	**8122 (4600)**

[1] Borewells are leased from other farmers in the region
[2] Unproductive animals include calves, dry animals, and bullocks

CSR system (n=25): HHs in this system owned an average of 1.7 (SD 0.7), a few of which were also functional in the winter season. Hence, some HHs in this system cultivated crops for two seasons in a year. The average cropped area per HH was 1.2 ha (SD 1.5 ha) in the monsoon season and 1.2 ha (SD 0.5 ha) in the winter season. The main crops grown were maize and cotton in monsoon and groundnut in the winter season. The total water used per HH was 2869 m^3 (SD 1335 m^3) for crop and small ruminant production per year.

In this region, farmers used groundwater from borewells to provide drinking to their animals because the surface water bodies were almost nil. The water consumption for adult sheep or goats was estimated to be 4.6 and 4.8 l/d in the monsoon and winter seasons and 5.9 l/d in the summer season. For lambs or kids, the values were 1.4 l/d in monsoon, 2.3 l/d for winter, and 3.9 l/d for summer. Therefore, the total drinking water was estimated to be 122.4 m³ (SD 86.8 m³) per HH for an average herd size of 8.3 (SD 5.6) TLUs per HH.

CD system (n=25): HHs in this system had the highest number of borewells, 4.9 (SD 2.9). Few of these borewells were in working conditions throughout the year, i.e. 3.2 (SD 1.8) in the winter and 1.2 (SD 1.9) borewells in the summer season. These HHs were into crop and dairy production, and the average groundwater usage per HH was estimated to be 8122 m³ (SD 4600 m³). A large share of this water was used to irrigate perennial green fodder. The food or cash crop cultivation (such as rice, maize, cotton, and vegetables) was limited to the monsoon season in the study year. The total cropped area per HH was 3.5 ha (SD 2.2 ha) for the whole year. The cropped area was dedicated to green fodder production in the winter and summer seasons. Farmers further indicated that winter and summer season crops were planned based on groundwater availability as they preferred to divert water for dairy production during these seasons.

In dairying, water was mainly used as drinking water for animals and livestock management activities such as cleaning and cooling animals in the summer. However, survey data indicated that only 48% of the HHs in the sample used water for the latter. Hence, from the total water used by the CD system (i.e. 8122 m³), only 869 m³ (SD 1261 m³) was used as drinking water for animals and livestock management activities.

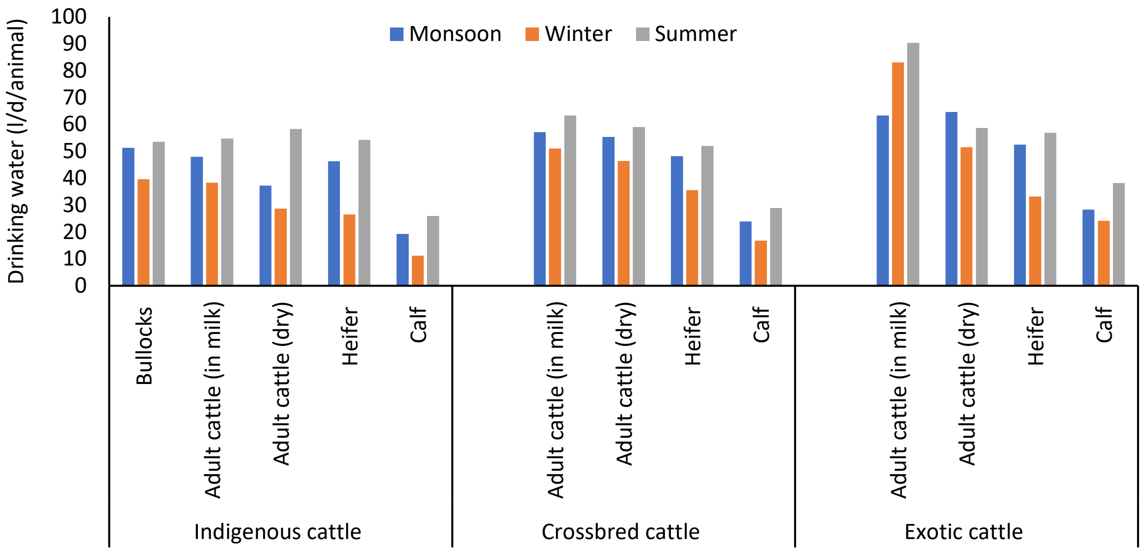

Figure 3: Average drinking water for large ruminants (l/d/animal)

Source: Longitudinal study 2015-16

Figure 3 shows the drinking water estimates for different cattle across breeds and physiological states. Among the dairy cattle breeds, the exotic cattle had the highest estimates of drinking water, followed by the crossbreds. We also found that a high amount of water was used for young animals, such as heifers, calves, dry animals, and non-dairy cattle like bullocks (See table 4). The herd size per HH ranged from 4 to 32 animals and averaged at 7.4 (SD 5.1) TLUs per HH. Of this herd size, an average of 4.3 (SD 3.1) TLUs were in milk, while 6.3 (SD 4.5) TLUs were unproductive animals.

3.2 Impact of different farming systems at the watershed level:

Table 5 presents the estimates of the domestic water use, the water used by the different farming systems, and the water availability at the village and the watershed level. The water balance table indicates that the water is in deficit at the village and watershed levels. The water balance at village level , however, differed between villages. This variation can be attributed to variation in proportion of farming systems between villages (see Table 1) and the population density in the villages. The high water deficit at the watershed level is explained by i) the excess water consumption by farming systems; ii) the region's high surface runoff volume (47.8 Mm^3/y) which also accounts for the high evapotranspiration in the region (1500-1950 mm); iii) and the low infiltration[3] capacity of water into the ground (i.e. 4.9 Mm^3/y) due to the region's geology (classified as the peninsular gneissic complex, i.e. hard rock formation), and the land use and cover (which is predominantly croplands) further aggravate surface runoff.

[3] Sikhija et al., (1996), show that the natural direct groundwater recharge in semi-arid regions of India with crystalline basement rock or peninsular gneissic complex is 3 -15% of the rainfall in the region

Table 5: Water Balance of the four villages and the watershed

	Thallakondapalle	Chandradana	Rampur	Veljal	Total at WS
WS area in the village (ha)	2718	1897	1604	3244	9463
Population (n x1000)	5157	2352	3255	5188	15952
Average rainfall over 5 years (mm/y)	687	687	687	687	687
Runoff volume[1] (Mm^3)	13.7	9.6	8.1	16.4	47.8
Groundwater Recharge[2] (Mm^3)	1.4	1.0	0.8	1.7	4.9
Water available (Mm^3/y)					
Surface water runoff	12.3	8.6	7.3	14.7	42.9
Water in surface water bodies[3]	2.5	1.7	1.5	2.9	8.6
Water not available as ground or surface water for farm production[4]	9.9	6.9	5.8	11.8	34.3
Water available for use (groundwater recharge + surface water bodies)	**3.9**	**2.7**	**2.3**	**4.6**	**13.5**
Water Use (Mm^3 /year)					
Domestic water use	0.10	0.05	0.03	0.07	0.25
Water used for farm production[5]					
Crop Without Livestock	1.1	0.4	0.5	1.2	3.2
Crop with Small Ruminants	0.2	0.06	0.05	0.1	0.4
Crop with Dairy	3.5	1.9	1.7	3.2	10.5
Other farming systems	0	0	0	0.04	0.05
Total Water Consumed (TWC) (Mm^3)	**4.9**	**2.5**	**2.3**	**4.6**	**14.3**
Water Balance (Deficit/Surplus) (Mm^3)	**-1.0**	**0.3**	**0.0**	**0.0**	**-0.8**

[1] Runoff Volume is the total amount of water expected in a given period of time (in this case, season) in the catchment (in this case, a watershed)
[2] Groundwater recharge is part of the runoff that gets infiltered into the ground and reaches the groundwater storage in the soil
[3] Assumption is that only 20% of the total surface water available is stored in surface water bodies as they are few and evapotranspiration in the region is high
[4] Is the water stored as soil moisture, evapotranspiration (1500-1950 mm/y), transpired by vegetation, and other surface runoff not captured as groundwater or in surface water bodies
[5] Extrapolated to the total number of households in the villages using government population census data based on the percentage of households per farming system in the sample

4. Discussion

This study, the coupled water use in different farming systems and the water balance at different scales (i.e. farming system, village, or watershed), provides a more complete understanding of the water available and water use in the region.

Among the three systems, the CD system used the highest water (8123 m^3/HH/y) than the CSR (2869 m^3/HH/y) and CWL (1833 m^3/HH/y) systems. Further, the livestock systems used more water to produce green fodder in the CD system and cultivation of other commodity crops (e.g. groundnut) in the CSR system (see Tables 2 and 4) than the CWL system. Groundnut production can complement small ruminant production since crop residues are used as feed (Heuzé et al., 2016). However, green fodder production in the CD system is a dedicated feed crop for dairying, which increases the water footprint of the system. The groundwater abstraction rate by all farming systems is more than the recharge rate of the watershed, and consequently a water deficit (see Table 5). The CD and CWL systems, were the largest water users as they constituted 86% of the HHs in the region.

Hence there seems to be an over-utilization of water in the region, which is possibly caused by three factors. First, there is a high focus on cultivating non-dryland crops such as rice, cotton, fruits, and vegetables. The cultivation of these crops not only directly increases the use of water in the region but also reduces the availability of crop residues for livestock. The shortage of crop residues has made the CD system to cultivate green fodder and invest (up to 80% of farming costs) in fodder from external markets (Kuchimanchi et al., 2022c). Hence the reduced availability of crop residues increases water use within the region and contributes to high virtual water use for fodder production outside the region (Kumar and Singh, 2008; Harika et al., 2016). Second, the increasing farm intensification and specialization imply reduced circularity in agriculture and sub-optimal integration of crop-livestock production within and between farms in the region (Kuchimanchi et al., 2021a, 2022c; Oosting et al., 2021). For instance, the CD system uses a large share of water to grow dedicated feed crops for livestock, such as green fodder (Table 4). In less specialized systems, this high-water footprint is often lower as the feed for livestock comes partly from crop residues grown on the same farm (e.g. CSR system) or from other farms in the region without livestock (e.g. CWL system). Third, certain management practices in the farming systems lead to high water use. For example, in the CD system, we found HHs having large herd sizes with many replacement animals, i.e. calves and heifers (Table 4), which comprised almost 85% of the TLUs per HH. Although keeping a large herd has benefits (e.g. manure availability or income from the sale of animals), a high number of female calves and heifers that take two years or more to become productive also require water resources. Similarly, in crop production, HHs in the region adopted management practices that increased or squandered water use. For instance, the higher use of inorganic fertilizers due to the lack of manure (Kuchimanchi et al., 2021a), causes soil hardening and loss of soil carbon levels, particularly in course textured semi-arid soils (Pahalvi et al., 2021; Edme et.al 2021). In dryland environments, both soil hardening and low soil carbon reduce the soil's water holding capacity, necessitating more irrigation (Plaza-Bonilla et al., 2015). In addition to this, the free power supply in the region also promotes unfavourable irrigation practices by farmers such as flood irrigation when not needed. Little adoption of conservative measures or cover crops is also an issue as the majority of the HHs are small and marginal farmers.

The over-utilization of water resources may have resulted in the indicated water scarcity. As a coping strategy, most HHs (i.e. the CD and CWL systems) have limited crop production to one season per year (Table 4), because borewells in the region do not function across the year and there is considerable variation in borewell pump discharge for summer (2000-5227 l/h) (Table 3). These findings also signify that over-utilization of water has led to groundwater scarcity in the region, which is in line with Sishodia et al., (2016) and the Central Ground Water Board reports (2017 & 2019-20). In addition to this, the high presence of croplands in the area (Kuchimanchi et al., 2021a) is another significant factor that causes groundwater depletion as it leads to high runoff due to a low vegetation cover (present study, Thomas and Duraisamy, 2019; Duraisamy et al., 2020). This phenomenon is illustrated in the water balance (Table 5), which shows a high runoff volume of 47.8 Mm^3 while the groundwater recharge was only 4.9 Mm^3 and only 8.6 Mm^3 is captured in surface water bodies at the watershed level (Table 5). These findings not only indicate the region's low groundwater recharge potential but also show that the region's ability to meet the water requirements for the current systems of production seems to have exceeded.

The high water-demanding practices leading to groundwater use and depletion, both in the region and across India, can be related to socio-economic conditions of farming communities, market demand, access to credit, agricultural and infrastructural subsidies, and development policies. Kuchimanchi et al. (2021b) showed that small landholdings and market demand for certain agricultural commodities impose farming strategies that are water-demanding on rural HHs to earn better incomes (e.g. cash or vegetable crops and dairy farming). Financial and credit systems may also often boost such water-demanding farm production pathways through loans to farm ventures with assumed cash flow and payment capacity (Ripoll-Bosch and Schoenmaker, 2021; Kuchimanchi et al., 2022c). Along with these, policies supporting smallholder agricultural production unintentionally worsen the situation further (Shiferaw et al., 2008; Fishman et al., 2014; Sishodia et al., 2016). For example, subsidies on power supply, irrigation infrastructure, and agricultural intensification accelerate land-use change and excessive water pumping in dry regions when coupled with market demand for specific agricultural produce, as they are usually water-demanding. Similarly, despite the large-scale promotion of water-efficient systems (drip and sprinklers) in India, Fishman et al. (2014) show that the potential of these systems to reduce the excessive extraction of groundwater is reduced due to the simultaneous increase in irrigated area. Lastly, watershed development program[4] could also be contributing to the same issue due to its incoherent program design. The program on one hand promotes agricultural intensification that is water-demanding

[4] India's most extensive development program for drylands focused on improving rural livelihoods through enhancing agricultural productivity by increasing the availability of surface and groundwater for agricultural production

and counterproductive to the soil moisture conservation measures that increases water availability within the same program. Similar findings have been reported by Batchelor et al., (2003), Joshi et al., (2004b), and Bouma and Scott (2006).

The situation described above may be the case across the dryland states of India as the same policies and development programs are implemented. Jain et al. (2021) further state that increasing groundwater depletion is expected to reduce cropping intensity by 68% in already groundwater-depleted regions. Hence, if current water-demanding agricultural pathways continue, India's food security might be in jeopardy and needs to be addressed. The further expansion or intensification of agriculture may also aggravate the social implications linked to depleting natural resources such as compromised incomes, high dependence on markets for inputs and feed, and increased indebtedness, all inducing marginalization, and vulnerability to climate change reported in studies by Reddy (2005), Shiferaw et al., (2008), Taylor (2013) and Kuchimanchi et al., (2021a, b, 2022c).Vaidhyanathan (2006) and Chinnasamy et al. (2019) have even found a link between groundwater depletion and farmer suicide-prone zones in some southern Indian states, where groundwater is the only source of irrigation for agricultural production. These insights imply that dryland watersheds have ecological limits. Agricultural production, therefore, needs to be determined by the region's water resources carrying capacity to mitigate the risk of desertification as reported in other dryland regions of the world (United Nations, 2011; IPCC, 2019).

Considering the above, the promotion of suitable farm strategies, modifying existing technological options and introducing new policies to reduce the over-use of water resources in food production is warranted. Farming strategies include the promotion of circularity in agricultural systems towards efficient use of natural resources (Muscat et al., 2021; Oosting et al., 2022) advocating feed and animal management options that are suitable to dry regions (e.g. control of herd size and structure, with optimal replacement strategies, choice of feed types and quality, improve animal health care and suitable animal breeds and purposes) (Descheemaeker et al., 2009; Kebebe et al., 2015; Tamou et al., 2018a, b) accentuate agronomic practices that maximize soil carbon levels and water holding capacity (e.g. soil and crop residue management, use of organic manures, and suitable cropping system designs) (Plaza-Bonilla et al., 2015; Giller et al., 2021).

The technological options involve the improvement of existing water conservation and use measures (e.g. watershed development, inland lake restoration, farm ponds, water-efficient systems) as water scarcity continues to grow, implying that the current measures may be inadequate. The first suggestion is to make climate science-based alterations in watershed development measures for better capture of surface runoff. This is needed as climate change is predicted to significantly influence the timing and magnitude of runoff, eventually impacting water supplies, water quality, and aquatic ecosystems of a watershed (Marshall and Randhir, 2008). The second would be to mainstream community engagement approaches and tools[5] in existing local governance structures to facilitate communities to manage their natural resources.

Regarding policies, we realize the necessity for a range of new policies targeting sustainable agricultural production in dryland regions. The policies propositions include the introduction of regulatory guidelines for the use of land and water resources (Shiferaw et al., 2008; Plaza-bonilla et al., 2015; Sishodia et al., 2015; Khair et al., 2019) as well as policies that incentivize the up-take of technologies and farm strategies for water conservation (Fishman et al., 2015; Shao and Chen, 2022; WRI, 2022). Region-specific agricultural commodity pricing and favorable financial and credit systems that promote the adoption of agro-ecologically suitable integrated crop-livestock production (Harding et al., 2021; Ripoll-Bosch and Schoenmaker, 2021). It is expected that such policies will address the unregulated use of water, reduce the over-utilization of water, and support suitable dryland farm development pathways.

This research aimed at gaining insight into how water is consumed in the study area by different farming systems, and what could be the implications of farming system development at watershed level. In the methodology, we combine different quantitative methods. One of the methods applied is the SCS-CN method, to estimate the runoff in the watershed. This method was initially developed to estimate direct runoff from rainfall in particular events (e.g. storms) and in particular locations in the United States of America (USDA, 1956). The convenience of the model, however, made it popular and was rapidly modified, improved and adapted for other locations (Ponce and Hawkins, 1996; Garen and Moore, 2007; Ajmal and Kim, 2014; Barlett et al., 2016) and for long-term studies, such as seasons or years rather than particular events (Mishra and Singh, 2004; Singh, 2017). This method has also been adapted to suit Indian conditions (suggested by the Ministry and Agriculture, Govt. of India, 1972; Singh, 2017). However, the method is still subject to criticism due to the several adaptations and because its oversimplification may compromise the accuracy of the results (see references above). Our study used several quantitative methods and combined several data sources. The scarcity of data, the assumptions and the generalities introduced in some of the calculations may lead to bias in the final figures here provided. For instance, population data relies on governmental census, which may not be accurate; water pomp discharge was based on experimental data from one season, while variations may occur across seasons; and, the assumptions and the

[5] https://www.fes.org.in/resources/tools/land-restoration/Composite%20Landscape%20Assessment%20and%20Restoration%20Tool%20(CLART).pdf
http://fes.org.in/source-book/groundwater-game-practitioners-manual.pdf
https://wotr-website-publications.s3.ap-south-1.amazonaws.com/156_Making_the_Invisible_Visible_A_Manual_for_Preparing_the_CoDriVE_Visual_Integrator.pdf

method applied may lead to a high runoff values (hence underestimating the total water available). However, we believe that the values fall within an acceptable range. Regarding the runoff value, for instance, literature indicates this to be high in arid and semi-regions due to the geology and high evapotranspiration rates (Rao et al., 2012). According to Sikhija et al., (1996), the natural direct groundwater recharge in semi-arid regions of India with crystalline basement rock or gneissic complex (such as in this study watershed) is 3-15% of the rainfall in the region (while our estimate is approximately 14%). Other studies in semi-arid regions also indicate low recharge, which is also the cause of high runoff (Rejani et al. 2015; Surinaidu et al., 2021). In all, due to the limitations of the methodology, the data scarcity and the assumptions, the results of this study should be considered as indicative rather than in absolute terms.

5. Conclusion

While intensification of agriculture has shown its benefits, particularly in increasing total food production, we also find that agricultural intensification in water-limited environments may lead to long-term social and ecological effects. In this study, we find that the current farming systems seem to use more groundwater than the region can infiltrate, likely causing groundwater depletion. Of the three main farming systems studied, the CD system used the most water for production, followed by the CSR system and the CWL system. However, the widespread presence of the CWL and CD farming systems in the region (comprising 86% of HHs) makes them the highest water users in the region. The main factors leading to the over-utilisation of water by these systems were the cultivation of water-demanding non-dryland crops, increased specialization of farming, and current agricultural management practices. The estimation of water use at the farm and the availability of groundwater at the watershed level shows that sustainable farming in dryland regions will need to be developed based on the region' water resources carrying capacity. We also realise that a range of factors aggravates groundwater use and depletion, such as socio-economic conditions of farming communities, market demand, access to credit, agricultural and infrastructural subsidies, and development policies. Hence, there is a need to promote agro-ecologically suitable farming strategies, improve the existing technological options and introduce new policies that reduce the over-use of water resources for sustainable agricultural production in dryland regions.

Chapter 5

Understanding the vulnerability, farming strategies, and development pathways of smallholder farming systems in Telangana, India

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Abstract

Climate change projections for the 21st century indicate an increase in India's already high number of food-insecure people. While considerable research on vulnerability to climate change exists, research about Indian smallholder farming systems, encompassing farming strategies and development pathways in this context, is limited. Hence, the current study examines the vulnerability of three smallholder farming systems, namely, (i) crop without livestock (CWL), (ii) crop with small ruminants (CSR), and (iii) crop with dairy (CD), in the context of climate change in Telangana, India. A mixed methods approach was used to conduct the research with a sample size of ten households per farming system. We found that households of different farming systems faced differential vulnerability due to variation in perceptions of climate change exposures, access to livelihood capitals, and their farming strategies. The CWL households were highly vulnerable to increased maximum temperature and erratic rainfall, while households that farmed crops and livestock were more vulnerable to the overall reduction in precipitation. Decision-making related to farming strategies was a complex process involving several factors, of which the availability of livelihood capitals provided by government programs was the foremost. Due to this, households of the different farming systems pursued divergent farming strategies, leading to varying types of adaptation and climate change resilience. Among the three farming systems, the households in the CWL system had the least access to all livelihood capitals. They also showed the highest vulnerability as their farm strategies only helped cope with immediate needs. The households in the CD system had access to all critical livelihood capitals, which facilitated opting for sustainable farming strategies. However, as these households depended on scarce groundwater resources for production, hence, their strategies only helped short-term adaption. Despite having access to limited capitals, the households in the CSR system adopted long-term adaptation strategies, which is attributed to them being a pastoral ethnic group. Lastly, despite having an integrated climate change policy, state-level development programs continue to focus more on agricultural intensification than on climate change adaptation. This stimulates farming strategies that are lucrative in the short term but endanger farming system resilience to climate change in the long term. Therefore, we recommend policy makers give high priority to climate smart development in state development programs and science-based evaluations of these programs to enable proper climate change adaptation in dryland regions that are inclusive of perspectives of different populations.

1. Introduction

The Intergovernmental Panel on Climate Change's Fifth Assessment Report (2014) on adaptation and vulnerability identified water shortage, food shortage, and heat-related mortality as key risks of climate change in Asia. Climate change will affect food security by the middle of the 21st century, with the most significant number of food-insecure people in South Asian countries, particularly India.

India has a large population of agrarian poor, who depend on natural resources for their livelihood. These populations are already vulnerable and exposed to non-climatic stressors and multi-dimensional inequalities, making them even more susceptible to climate change. Over the past two decades, therefore, considerable research has been carried out in India, covering vulnerability, farmers' adaptation, and policies regarding climate change adaptation (Taylor, 2013; Banerjee, 2014; Dubash and Jogesh, 2014; Singh et al., 2014; Udmale et al., 2014; Dhanya and Ramachandran, 2016; Maiti et al., 2017; Kuchimanchi et al., 2019; Singh et al., 2019a). Studies addressing livestock and climate change have also been conducted, mainly reviewing livestock systems, population dynamics, sustainability of livestock systems, and recent trends and prospects of animal production for developing countries at high aggregation levels (Thornton et al., 2009; Nardone et al., 2010; Thornton, 2010; Alemayehu and Fantahun, 2012; Weindl et al., 2015).

However, all these studies looked at crop and livestock farming systems in isolation. Research about vulnerability, farming strategies, and development pathways at the regional level, encompassing different farming systems and their interaction, is limited, in general and in India. Such studies are important since smallholder farming systems, particularly in dryland regions, compete with each other and with other land users for water and land. Often, farmers in dryland regions intensify their crop and livestock production to cope with the conditions and to eke out a living. However, it is still unclear how climate change interacts with the intensification of production and interaction among smallholder farmers (Nardone et al., 2010), and such regional level studies may provide insights.

The present study aims to better understand the vulnerability of three smallholder farming systems that provided consistent agricultural incomes to households (HHs) in the study region, namely, (i) crop without livestock (CWL), (ii) crop with small ruminants (CSR), and (iii) crop with dairy (CD) systems, in the context of climate change along with their farming strategies and development pathways. Here, we focus on climate change vulnerability, coping and adaptation strategies applied by HHs of different farming systems, and the sustainability of their development pathway within the socio-ecological system.

To achieve the above, we use the following theoretical framework and definitions. In line with Gallopın et al. (2006), we first define a socio-ecological system (SES) as a system that includes societal (human) and ecological (biophysical) subsystems in mutual interaction. The SES can be specified for any scale, from the local community and its surrounding environment to a larger global system. For vulnerability, we use the concept of Turner et al., (2003): "**vulnerability** rests in a multifaceted socio-ecological system which is exposed to hazards along with dynamic and nonlinear processes operating at different spatiotemporal scales". The most often-cited IPCC definition of vulnerability is the degree to which a system is susceptible to and cannot cope with adverse effects (of climate change). Turner's framework was chosen because it helps analyze vulnerability and related aspects in a concise form that includes the larger systemic character of the problem. The framework consists of three broad elements: (i) linkages between human and biophysical conditions and processes operating on the system in question; (ii) perturbations and stressors that emerge from these conditions and processes; and (iii) the SESs of concern in which vulnerability resides, comprising of exposure, sensitivity, and resilience. **Exposure** refers to the nature and degree to which a system experiences environmental or socio-political stress. **Sensitivity** is the degree to which a SES is modified or affected by perturbations (Adger, 2006). **Resilience** is evaluated in terms of the changes a system can undergo due to exposure while continuing to remain within the set of natural or desirable states. Resilience is the dynamic result of the response of an SES to a perturbation, which can be short-term **coping** or long-term adjustment **adaptation**. This adaptation and the associated **adaptive capacity** is the ability of a system to evolve in order to accommodate environmental hazards or policy change and to expand the range of variability with which it can cope (Adger, 2006). Further, to assess the adaptive capacity of rural HHs, we used the Sustainable Livelihoods Framework (DFID, 1999) approach as it advocates that HH level livelihood objectives and strategies are shaped by how people use their asset base, which we refer to as capitals here. The livelihood framework identifies five core asset categories or types of capital, i.e. natural capital, physical capital, financial capital, social capital, and human capital. **Natural capital** is the term used for the natural resource stocks from which resource flows and services useful for livelihoods (e.g. land, water, forests, marine/wild resources, air quality) are derived. **Physical capital** comprises the basic infrastructure and producer goods needed to support livelihoods (e.g. affordable transport; secure shelter and buildings; adequate water supply and sanitation; and clean, affordable energy. **Financial capital** denotes the financial resources people use to achieve their livelihood objectives such as savings, liquid assets like jewelry, credit, and subsidies). **Social capital** refers to the social resources people use to make livelihoods, such as networks, associations, cooperatives, and memberships in formal/informal associations, which bring in connectedness and cooperation. **Human capital** represents skills, knowledge, ability to labor, and good health.

In this paper, we first describe the socio-economic policy and the environmental contexts and processes operating in the study region (sections 3.1, 3.1.1, and 3.1.2). We then analyze how the HHs in the three farming systems perceive climate change exposure and what sensitivity they face in this coupled human-environment system (sections 3.2, 3.2.1, and 3.2.2). We then explore the different development pathways that the farming systems choose, in terms of coping and adaptation, in sections 3.3.1 and 3.3.2. In the discussion, we reflect upon the drivers behind farm strategy choices, associated vulnerability to climate change, and what it means for the economic and ecological sustainability of the farming systems studied herein.

2. Material and Methods

2.1 Study sample and location

The study was conducted in two watersheds, located in the *Rangareddy* and *Nagarkurnool* districts in Telangana, India (Figure 1). Agro-climatically, both watersheds fall in the Deccan Plateau (Telangana) and Eastern Ghats agro-ecological subregion (AESR) 7.2, which is part of the Southern Plateau and Hill region. AESR 7.2 is broadly characterized by deep loamy and clayey mixed red and black soils with medium to very high available water capacity, and duration of growing seasons

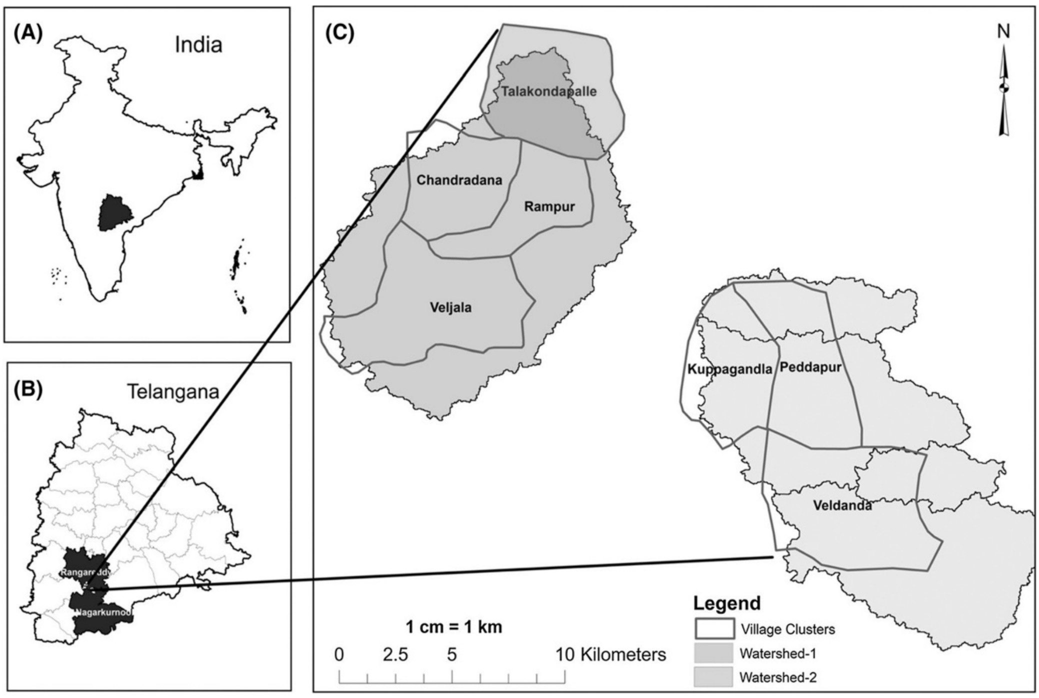

Figure 1: Location map of the study region in India.
(A) The location of the state of Telangana in India. (B) The two districts where the watersheds are located within the state of Telangana. (C) The two watersheds, village boundaries and the study village Thalakondapalle (highlighted in gray). Source: ISRO BHUVAN portal
(htpps://bhuvan.nrsc.gov.in/bhuvan_links.php , accessed 2016)

ranging from 120 to 150 days. The aridity index (AI) of the region is between 0.2 ≤ to < 0.5 (Rao et al. 2019) and is therefore classified as semi-arid. The region is drought-prone as it falls in the scarce rainfall zone, with an annual rainfall of 500–700 mm, which follows a seasonal pattern (Gajbhiye and Mandal, 2000; Manickam et al., 2012).

This study is a follow-up to a previous study characterizing farming systems in the region (Kuchimanchi et al., 2021c). The region has five farming systems (Table 1). In the present paper, we study the vulnerability to climate change of only three farming systems, i.e. the CWL, CSR, and CD systems, because only these systems provided a consistent agricultural income to the HH in the region. The 'landless with livestock' and 'crop-diverse livestock farms' largely depended on off-farm income. A two-step sampling process was conducted. First, the village where all farming systems were present was selected in the watersheds, i.e. *Thalakondapalle*. Next, within the selected village, 10 HHs per farming system were selected randomly. Within these HHs selected, care was taken that all farm sizes and all caste groups in the region were present - as these could be determinants of vulnerability (Table 2). The farm sizes considered were large farms (>4 ha), medium farms (2–4 ha), small farms (1–2 ha), and marginal farms (up to 1 ha).

The caste system in India is a social hierarchical system that has its origins in ancient India. This system, however, has been transforming since medieval times, including social reforms in modern India (de Zwart 2000; Bayly 2001). Nevertheless, stratification continues to exist in various forms. Currently, according to the government of India classification, castes and ethnic groups are categorized into four main categories, i.e. forward castes (FC), backward castes (BC), scheduled castes (SC), and scheduled tribes (ST).

In brief, the CWL farming system is characterized by rainfed crop farming as borewell irrigation was limited post-monsoon season. Hence crop farming is restricted

Table 1: Distribution of farming systems across the sample watersheds (n)

Farming system	Study village							
	Thalakonda-palle	Chandra-dana	Rampur	Veljala	Peddapur	Kuppa-gandla	Veldanda	Total HHs
CWL system	304	189	147	195	145	165	181	1326
CD system	232	193	102	115	166	119	136	1063
CSR system	32	16	8	13	34	49	13	165
LWL system	22	10	85	16	7	39	9	188
CWDL system	1	1	0	7	6	0	8	23

Source: Farming systems characterization database (Kuchimanchi et al. 2021c)
CWL, crop without livestock; CD, crop with dairy; CSR, crop with small ruminants; LWL, Landless with livestock; CWDL, Crop with diverse livestock

Table 2: Distribution of farm sizes and social groups across farming systems in the study village

Farming system	# HHs (%)	Farm size[1] (%)	Social Groups[2] (%)
CWL system	304 (53.5)	Large farms (8.6)	FC (12.5)
		Medium farms (20.1)	BC (45.5)
		Small farms (42.8)	SC (34.2)
		Marginal farms (28.6)	ST (7.9)
CSR system	32 (5.6)	Large farms (25.0)	FC (3.1)
		Medium farms (50.0)	BC (84.4)
		Small farms (18.8)	SC (12.5)
		Marginal farms (6.3)	ST (0)
CD system	232 (40.8)	Large farms (13.4)	FC (6.9)
		Medium farms (37.9)	BC (36.2)
		Small farms (31.5)	SC (27.6)
		Marginal farms (17.2)	ST (29.3)

[1]Large farms (>4 ha), medium farms (2–4 ha), small farms (1–2 ha), and marginal farms (up to 1 ha)
[2]FC- Forward caste, BC- Backward Caste, ST – Schedule Tribes, SC- Schedule Caste
CWL, crop without livestock; CSR, crop with small ruminants; CD, crop with dairy
Source: Farming systems characterization database (Kuchimanchi et al. 2020c)

to one agricultural season. These HHs, therefore, relied more on off-farm income such as wage labour in government and private construction sites, transportation services, and hotels. This system had the highest number of HHs (53.5%), and the majority were small farms (42.8%). The CSR farming system is characterized by rainfed and irrigated crop farming with sheep or goat rearing. HHs rearing sheep rarely depended on off-farm labour. However, in contrast, HHs rearing goats frequently depended on off-farm labour for additional income. Only 5.6 % of the HHs were present in this system, and the majority of them had medium-sized farms (50%). The CD farming system is characterized by irrigated crop cultivation and dairying production with high market-orientation. These HHs had guaranteed water resources, better agricultural farm equipment, and were economically self-sufficient. This system had the next highest presence of HHs (40.8%), and medium farms were a majority (37.9%)

Further, we found that all caste groups were present in all farming systems, owned land, and were involved in agriculture in the region (Table 2). Among the groups, the BCs (44%) dominated in presence, followed by SCs (30.3%), STs (16.4%), and FCs (9.3%). The region has two ethnic groups, historically specialised in livestock rearing. The first was a traditional livestock-keeping community called the "*Gollas*" classified as BCs (Murty, 1993). The second is the "*Banjaras*," who are STs who were nomadic pastoralists in the past (Roy, 2010) but have now adopted sedentary agriculture.

2.2 Methodological framework

A combination of two methods, i.e. a HH survey followed by focus group discussions (FGDs), was used to capture the various facets of vulnerability and farming strategies and pathways associated with the HHs. While the survey helped quantify and measure certain aspects for better justification, the FGD data offered more in-depth knowledge, providing a better understanding of ground realities, particularly of short- and long-term adaptation and farmer strategy choices. The research work was conducted from February to June 2017.

As a first step, we performed a HH survey across the 30 selected HHs using a survey format that covered three principal aspects: (i) the status of livelihood capitals across all relevant HH activities, i.e. crop production, livestock production, and non-farm and forest-dependent activities; (ii) perceptions of climate risks and impacts; and (iii) strategies taken to manage these risks and impacts.

Next, we organized three FGDs, one for each of the three farming systems, and invited two to three members from each HH included in the survey. Therefore, each FGD had around 20–25 participants representing men and women of all age groups. A semi-structured questionnaire was used to guide the discussions in the FGDs. The discussions revolved around perceived climate change exposure, impacts faced, farming strategies adopted, and all factors that influenced the farm strategy choices. Each FGD lasted for 3–4 hours, and the discussions were conducted in the local language '*Telugu*', which is also the native- tongue of the first author. Care was taken to organize the FGDs in such a manner that all participants could share their opinions and experiences freely. Key points discussed in the FGDs were documented on charts to spot linkages and identify possible drivers of change. Similarly, climate change exposures and the months perceived as most risky and troublesome were diagrammed to help capture details.

As the last step, a desk review of the national and state climate-change policy contexts was undertaken. This was done to understand the connections between national-level policies to the human and biophysical (environmental) processes operating within the study region that influence vulnerability.

2.3 Data analysis

The survey data were organized in MS Excel based on three principal aspects used in the HH survey, i.e. (i) the status of livelihood capitals, (ii) perceptions of climate risks and impacts; and (iii) strategies taken to manage these risks and impacts to identify trends and patterns. We also quantified the number of responses per farming system to determine high exposure (≥8 responses), medium exposure (5–7 responses), and low- exposure (<5 responses) on the perception of climate exposure (Table 3). A similar method was used to determine the level of impact of the identified climate change exposure on the different farming systems (Table 4), where ≥8 responses meant high impact, 5–7 responses meant medium impact, and <5 responses meant low impact. On the same lines, the status of the livelihood capitals (Table 5) was also assessed as high, medium, and low access or ownership based on the responses. High indicated a score above 8 responses, showing that the majority of the farmers owned or had access to the particular capitals, the medium was a score between 5–7 responses, and low was a score of <5 responses. Finally, the adoption of farming strategies (Table 6) was also scored based on the number of responses, where ≥8 responses indicate high adoption, 5–7 responses indicate medium adoption, and <5 is low adoption. These data were later corroborated with the FGD data to develop consistent case stories of each farming system related to their vulnerability and adaptation.

3. Results

3.1 Socio-economic and policy context

Agriculture, with its allied sectors, is the largest source of livelihood in India. Seventy percent of India's rural HHs depend primarily on agriculture for their livelihood, with 82% of farmers being small and marginal. While Indian agriculture has achieved self-sufficiency in grain production, it has become intensive, and serious sustainability issues such as increased stress on the country's water resources, desertification, and land degradation have emerged (FAO, 2019). To sustain India's rapid economic growth, many rural development policies and programs exist that address multiple objectives to improve the social and economic standards of rural HHs and natural resource management. Among these, the Government of India formulated the National Action Plan on Climate Change (NAPCC) in 2008, focuses on climate change adaptation. The NAPCC encompasses eight national missions, among which the National Water Mission (NWM), the National Mission for Sustainable Agriculture (NMSA), and the State Level Action Plan on Climate Change (SAPCC) are of relevance to this study. However, an exploration of these policies indicates that, though the missions are integrated and climate-centric at the central level, the interventions at the state–level are aimed at livelihood and regional economic development and not on climate change adaptation. For example, the Rainfed Area Development (https://nmsa.dac.gov.in/Default.aspx) a component of the NMSA, is formulated in a 'watershed plus' framework. It reaches rural HHs through national-level umbrella programs[1] that focus on holistic agriculture development, allied sectors, and water management and are customized at the state level. However, we find that the interventions concerning crop-livestock production do not reflect climate smart measures and tend to promote green and white revolution technologies or are

[1] RKVY: https://rkvy.nic.in/ , PMKSY: https://pmksy.gov.in/AboutPMKSY.aspx

intensification-oriented. We also find minimal adoption of interventions advocated by the Central Research Institute for Dryland Agriculture[2] or the SAPCC of Telangana. This situation may be due to political dynamics and lack of collaboration among policymakers and research, which negatively influences climate change adaptation at the local level. This is because the livelihood capitals available at the local level come through these programs, schemes, and subsidies, which tend to influence farm strategies and adaptation pathways of rural HHs that are not necessarily climate adaptive.

3.2 Environmental context

Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and further by 2°C (IPCC 2018). Chapter 7 of the IPCC AR5 WG II states that there is a high probability that developing countries will be negatively affected by climate change, particularly food security. This is also predicted for India, where 69% of the land area is dryland (arid, semi-arid, and dry sub-humid). India is among the most drought-prone regions of the world (Ajai et al., 2009; Banerjee, 2014), and the above-mentioned transitions toward intensive agriculture continue to progress (Amjath-Babu and Kaechele, 2015; Behera et al., 2016; Gathorne-Hardy, 2016; Kuchimanchi et.al., 2020b submitted). According to IPCC's Climate change and Land report (2019), such transitions to intensification of land and water use will enhance land degradation, water scarcity, and food insecurity in drylands. The World Bank report (2012) "Turn Down the Heat" indicates that India is already facing water stress conditions, in the form of droughts and floods, in many parts of the country. In the future, unusual and unprecedented spells of hot weather are expected to occur more frequently. Whereas India's summer monsoon is expected to be highly unpredictable, with frequent droughts in some parts of the country (IPCC 2018, Rao et al., 2019). These climate change phenomena will further impact agriculture, with already falling water tables. Moreover, Reddy et al. (2014) stated that the projected climate change for southern Telangana (the study region) coincides with increasing crop water requirements. Hence, the future context of agriculture portends higher water requirements, less reliable precipitation, and intensified groundwater exploitation.

3.3 Smallholder farming systems and vulnerability to climate change

3.3.1 Farming systems and perceived exposure to climate change in the region

Both FGDs and the HH survey revealed that farmers of all three farming systems recognized a change in climate since the year 2000. The main climate change exposures

[2] the lead institute and national nodal point for the National Innovations in Climate Resilient Agriculture

perceived by the respondents (in decreasing order of frequency) were increased maximum temperature, erratic rainfall, reduced precipitation, increased frequency and length of dry spells, delayed onset of monsoon, warmer winters, and increased frequency of high-intensity rainfall (Table 3).

A high number of farmers (both genders) from all farming systems perceived increased maximum temperature, delayed onset of monsoon, and dry spells as climate change exposures. CWL farmers highlighted erratic rainfall most frequently, whereas CSR and CD farmers noted reduced precipitation most frequently. Less than half of the farmers mentioned warmer winters and high-intensity rainfall. Respondents further added that, at times, these climate change exposures occurred simultaneously.

Table 3: Farmer perceptions of major climate change exposures in the region

Farming system	Types of climate change exposures						
(n =10/system)	Increased maximum temperature	Delayed onset of monsoon	Dry spells	Erratic rainfall	Reduced precipitation	Warmer winters	High-intensity rainfall
CWL system	H	H	H	H	M	M	M
CSR system	H	H	H	L	H	L	L
CD system	H	H	H	L	H	L	L

Source: Household survey

Note: H: high exposure, score ≥ 8 responses; M: medium exposure, score 5–7 responses; L: low exposure; Score <5 responses; CWL, crop without livestock; CSR, crop with small ruminants; CD, crop with dairy

3.3.2 Farming systems and perceived sensitivity to climate change in the region

The major effects of climate change exposure identified by farmers are presented in Table 4. The different climate change exposures had different levels of impact on the different farming systems. For example, CWL farmers, who only produced crops, reported decreasing crop yields, increasing disease and pest attacks, crop losses, heating up of soil, and decreasing groundwater levels as the main effects of climate change that impacted them greatly. In this aspect men spoke about overall income loss, while women referred to negative impacts on food security and on other basic HH needs. The CWL farmers further mentioned a medium impact on human health due to the increase in maximum temperature and warmer winters. The increase in maximum temperature hampered the ability to work for extended hours, especially for women as they are the main workforce in vegetable or cash crop cultivation. Many respondents noted that in this situation they were not able to offset income loss through more alternative wage work or hiring of farm machinery. Higher pest and disease incidence, an effect of erratic rainfall, also increased production costs, e.g. investments in pesticides and fertilizers. Further, while groundwater depletion is an

Table 4: Level of impact of climate change exposure on different farming systems

Climate change impacts	CWL system farmers	CSR system farmers	CD system farmers
Decrease in crop yields	H	M	H
Increase in disease and pests in crops	H	L	M
Increase in crop losses	H	L	M
Inability to grow certain crops	-	-	L
Increase in soil heating	H	L	M
Decrease in vegetation in common property resources	M	H	H
Decrease in crop residues	-	H	M
Increase in diseases in animals	-	H	L
Increase in heat stress in cattle	-	-	M
Decrease in groundwater levels	H	L	H
Decrease in surface water bodies	-	H	-
Increase in health issues in humans	M	-	-

Source: Household survey
Note: H: high impact, score ≥ 8 responses; M: medium impact, score 5–7 responses; L: low impact, score < 5 responses; CWL, crop without livestock; CSR, crop with small ruminants; CD, crop with dairy

existing problem in the region, changes in climate such as reduced precipitation accentuate the issue. Thus, inadequate groundwater limited the area under crop production, which reduced crop residue availability and ultimately affected livestock rearing. All these factors contributed to the loss of income and food security, especially for women and children.

For CSR farmers, the major effects of climate change reported were increased incidence of animal diseases, reduced availability of crop residues, decreased availability of surface water bodies, and reduced vegetation in common property resources (CPRs). While these problems relate to non-climatic factors, climate change exposure compounded the impacts. According to the farmers in this CSR system, these climate change effects impacted small ruminant production considerably because the once zero-to-low input production system had to be transformed into a high-input system. Both men and women noted that the grazing hours are longer. They also shared that the higher production costs are due to increased expenses for animal health care, the need to purchase fodder, lease lands, and borewells for grazing and watering, respectively. However, for women and poor HHs who cannot afford these additional investments, reduced livestock rearing, and become deprived of critical nutrients and income.

CD farmers listed out many effects but underscored only three that caused the most distress, namely, groundwater depletion, lowered crop yields, and decreasing vegetation in CPRs. They reported that over time these climate change effects forced them to increase their investments in agriculture, with no guarantee for good returns. They further added that climate change has made it difficult to grow certain crops, e.g. rice and sorghum. This forced them to produce cash crops such as cotton and maize, which provide less food and crop residues for livestock.

3.4 Farm livelihood capitals and strategies

Within the above context, the current section describes (i) how farmers belonging to the three farming systems have access to livelihood capitals and (ii) the different strategies that make up the farming HH's "resilience."

3.4.1 Three farming systems and their access to livelihood capitals

Table 5 presents the status of livelihood capitals for the three farming systems in the region, as emerging from the HH survey. The scoring revealed that farmers in the CWL system had the lowest ownership of key natural capital indicators, i.e. land, livestock ownership, access to water, irrigated land, forest, and fodder resources for livestock. The majority had to leave a considerable part of their cropland seasonally fallow, as they had limited capacity to lease additional agricultural land. All the CWL farmers cultivated exclusively cash crops and used solely inorganic inputs as they did not own livestock. Factors that made rearing livestock difficult were reducing CPRs, inadequate water resources, lack of additional labor, and state-imposed ban on forest grazing. CWL HHs also had the least physical capital, particularly access and ownership to irrigation and agricultural infrastructure. They owned the lowest number of borewells, which were merely seasonally functional. They predominately owned manual implements and rented farm machinery and bullocks, thereby incurring relatively high crop production costs. Regarding financial capital, the CWL HHs were most dependent on wage labor and crop insurance. Interestingly, the majority of the CWL HHs were members of farmer producer organizations, informal farmers' groups, and women self-help groups (WSHGs) i.e. social capital. With respect to human capital, most of the CWL farmers had very limited knowledge of sustainable farm management and were the least educated. However, the majority had multiple skillsets, i.e. farm-, off-farm-, and traditional occupational skills, at the HH level.

Among the CSR farmers, some owned irrigated land, while others did not. Like the CWL farmers, these farmers also left their croplands fallow in one or more agricultural seasons, particularly in bad rainfall years. Regarding cropping patterns, these farmers cultivated cash crops that produced crop residues, such as maize or groundnut. They used both inorganic fertilizers as livestock manure for crop production as they owned livestock. Shrinking CPRs and denied access to forest lands for grazing impacted the CSR farmers the most, and hence, the majority leased croplands for their small ruminants. Some purchased fodder from markets when

Table 5: Farming systems and their livelihood capital status

Livelihood capital indicators	Status of livelihood capitals per farming system		
	CWL farmers	CSR farmers	CD farmers
Natural capital indicators			
Land use pattern			
Irrigated lands	L	M	H
Leased lands	L	H	M
Seasonal fallow lands	H	H	L
Cropping pattern			
Cash crops only	H	M	L
Cash crops with crop residues & green fodder	NA	L	H
Livestock resources			
Mixed livestock	NA	L	L
Specialized livestock farming	NA	H	H
Natural water resources for livestock			
Natural water bodies, seasonal	NA	M	NA
Forest resources			
Access to fodder & non-timber forest produce	L	L	NA
Fodder resources			
Common property resources	-	L	NA
Grazing on leased land	NA	H	M
Purchase fodder from markets & other farmers	NA	M	H
Reduce crop production and use land for grazing	NA	M	H
Grow green fodder	NA	L	H
Physical capital indicators			
Irrigation infrastructure			
Own borewells, functionality	L	M	H
Lease borewells	nil	M	L
Own water-efficient system	nil	nil	L
Agriculture infrastructure			
Manual implements	H	M	-
Bullocks (rented)	M	M	L
Farm machinery (rented)	H	H	L
Post-harvest structures	L	L	M
Financial capital indicators			
Crop & livestock insurance	M	H	L
Crop & livestock subsidies	M	H	M
Formal and informal credit	H	M	H
Investments in animal health	NA	H	M
Wage labor	H	L	NA
Social capital indicators			
Membership in farmers' Groups/animal breeders' Societies/women's self-help groups	M	L	M
Human capital indicators			
Knowledge on sustainable crop–livestock management			
Knowledge levels	L	-	M
Have knowledge, do not practice	-	H	L
Have knowledge, limited practice	L	L	H
Access to climate information services	L	L	H
Presence of traditional knowledge	L	H	L

Table 5: Farming systems and their livelihood capital status (continued)

Livelihood capital indicators	Status of livelihood capitals per farming system		
	CWL farmers	CSR farmers	CWL farmers
Human capital indicators (continued)			
Alternate skill sets/farm/off-farm			
Only farm-based skills	H	H	H
Have both farm and off-farm skills	H	L	L
Traditional occupational skills	L	H	L
Education			
School dropouts	H	H	L
Completed schooling	L	L	M
Higher education	L	L	M

Source: Household Survey
Note: H: high access, score ≥ 8 responses; M: medium access, score 5–7 responses; L: low access, score < 5 responses; CWL, crop without livestock; CSR, crop with small ruminants; CD, crop with dairy

needed. Due to reduced precipitation and dried-up surface water, CSR farmers faced limited availability of water for livestock. The CSR farmers themselves owned very few borewells, which were mostly seasonally functional, but all were able to lease borewells to overcome the problem of water scarcity. Regarding the financial capital, CSR farmers reported the highest dependence on crop/livestock insurance and subsidies (e.g. investment support schemes, seed, and fertilizer inputs). Some of them also indicated dependence on wage work but only under difficult circumstances or when in need of extra finances. Regarding human capital, most of the CSR farmers had knowledge of sustainable crop-livestock farming practices but did not practice them. Almost all farmers reported having traditional knowledge of sheep rearing.

The CD farmers had the best access to all livelihood capitals. Regarding natural and physical capitals, their lands were fully irrigated. They owned multiple functional borewells throughout the year, resulting in better incomes. This enabled them to grow green fodder and purchase fodder and crop residues from markets. They also leased lesser land for grazing than the CSR farmers. They owned more farm machinery regarding agricultural infrastructure and used a mix of inorganic fertilizers and livestock manure. The CD farmers were also the sole farmers using water-efficient systems. As for human capital: most CD farmers had high levels of education, knowledge of sustainable crop-livestock management, and good access to climate information services.

We found that all farming systems had HHs from all social groups and farm sizes. However, SCs and HHs with small farms had a higher prevalence in the CWL system, in which HHs had the lowest livelihood capitals. The CD and CSR systems were dominated by BCs and HHs with medium-sized farms and had more access to livelihood capitals. This included the STs; though lowest in the caste hierarchy, they had a higher prevalence in the CD system. Similar was the case with BCs, who had the highest presence in the CSR system (Table 2). Hence, social groups with ethnic identities linked to livestock rearing (the STs – *Banjaras* and the BCs - *Gollas*) seemed to fare better, as shown by their relatively good access to livelihood capitals.

Concerning women, the impact was mixed. On one side, having higher social capital increased their access to livelihood capitals, providing loans, livestock assets, and technologies through the government WSHGs program. However, climate change impacts on crop-livestock production (Table 4) that caused income loss made loan repayment difficult, especially for the WSHGs formed by lower caste women compared to the FC women.

3.4.2 Farming systems and their farming strategies

CWL farmers reported that their choice of cash crop production (notably cotton) over food crops had been an unavoidable strategy (Table 6). Cash crops had higher market values and guaranteed a better income to cover immediate needs than food crops. It enabled them to cope with decreasing land sizes. For example, CWL farmers mentioned that cotton production saved time and enabled them to take up other livelihood activities. The cotton crop required limited fieldwork and provided reasonable yields even under rainfed/less irrigated conditions. Some CWL farmers noted that they tried to simultaneously grow cash and food crops but discontinued it as the income earned was insufficient. Furthermore, as climate change exposure led to variable yields, farmers became highly dependent on intermediaries, willing to buy low-quality and low quantities of produce. As the CWL HHs now grew only cash crops, they became highly reliant on the markets and the public food distribution system for their food needs.

To enhance crop productivity, CWL farmers increasingly used inorganic inputs. Most sampled farmers knew that high use of inorganic fertilizers was not sustainable, but they claimed they had no other option as they lacked livestock and the means to purchase manure. They did, however, apply farm mechanization, using tractors and crop harvesters. This increased production costs, but they noted that it enabled HHs to work extended hours under increasingly high temperatures. CWL farmers increasingly resorted to government subsidies and formal and informal credit to pay the high production costs. As crop production became troublesome, many CLW farmers started to lease out their fallow croplands as a source of revenue. In difficult circumstances, these farmers reported selling assets as one of their main strategies to cope and manage loan cycles. Respondents noted this was an effective strategy to overcome temporary risks but marginalized them over time. As crop production had become highly unpredictable, increased engagement with wage work became a crucial

Table 6. Farming strategies adopted by respondents of different farming systems

Farming strategies to cope with effects of climate change	CWL farmers	CSR farmers	CD farmers
Crop production related			
Shifted to commercial crops	H	L	L
Shifted to cash crops with residue	-	H	H
Partially shifted to cash and food crops	L	-	M
Increased usage of inorganic inputs	H	M	L
Adopted farm mechanization	H	H	H
Water-use related			
Invested in borewells	M	M	H
Leased borewells for livestock		H	-
Adopted water efficient system	-	-	M
Alternative crops, less water intensive	-	-	M
Reduced crop cultivation, diverted for dairying	-	-	H
Livestock production-related			
Improved management of livestock	-	H	H
Improved fodder management	-	L	H
Left crop lands fallow for grazing	-	H	H
Purchased fodder from markets/other farmers	-	H	M
Leased land for grazing	-	H	H
Increased investment animal health care	-	H	H
Infrastructure for Livestock	-	L	M
Food, assets, and livelihood related			
Increased dependence on govt subsidies	H	H	H
Used crop insurance/livestock insurance	M	H	L
Dependence on formal/informal credit	H	M	H
Increased dependence on wage work	H	L	-
Migration	L	-	-
Leased out land for others	H	-	-
Sold assets	H	-	L
Dependence on middlemen	H	H	M
Increased dependence for food on markets and public food distribution system.	H	H	M

Source: Household survey and FGDs.

Note: H: high adoption, score ≥ 8 responses; M: medium adoption, score 5–7 responses; L: low adoption, score < 5 responses; CWL, crop without livestock; CSR, crop with small ruminants; CD, crop with dairy

livelihood strategy. However, to their dissatisfaction, high daytime temperatures impeded more wage work, causing health issues.

Furthermore, as agricultural work opportunities were inadequate, HHs also resorted to migration. Lastly, though the CWL HHs had the highest social capital it did not increase their networking or knowledge levels. Low education levels (human capital) compounded by low financial capital rendered it ineffective.

Like CWL farmers, CSR farmers also grew cash crops. They opted for maize and groundnut crops as the cost of production was low and provided crop residues for livestock. Their use of inorganic fertilizers was relatively low as they owned livestock. Like the CWL farmers, the adoption of farm mechanization was a well-known strategy to manage crop and small ruminant farming. CSR farmers showed high concern for their small ruminants. To cope with reduced CPRs for grazing and fodder scarcity, CSR farmers leased croplands and bought crop residues from other farmers and markets. In times of water shortage and unpredictable or delayed monsoons they also deliberately left croplands to fallow for more grazing area. To ensure drinking water for their livestock, CSR farmers chose not to invest in new boreholes, as the success rate to get a functional borewell was low, and they instead leased borewells from other farmers. This, however, made them dependent on the willingness of other farmers to share water with them. CSR farmers reported heavily investing in animal health care because climate change exposure led to many health issues. They complained, however, that animal health services hardly catered to small ruminants. CSR farmers in this region had always relied on middlemen for animal sales and still did. Further, like the CWL farmers, CSR farmers also highly depended on government subsidies and insurance, and they obtained their food from the markets and the public food distribution system.

CD farmers displayed rather distinctive farming strategies. They cultivated cash crops that simultaneously provided crop residues for feed and even grew food crops. This reduced their dependence on the public food distribution system. CD farmers owned some farm machinery and demonstrated the highest level of farm mechanization. They claimed it was an effective strategy to manage the labor shortages and increasing wage labor costs experienced in the region. They, however, invested heavily in new borewells, though they were aware that continuous digging of new borewells was not a sustainable option. Hence, structural water shortage stimulated them to adopt water-efficient systems, e.g. drip irrigation. Many respondents noted that they reduced the cropping area to save water for their dairy livestock, as the latter guaranteed a more stable income. CD farmers forwarded various strategies to manage their livestock and fodder scarcity, such as buying locally bred exotic cattle, relocating cattle to areas with more fodder and water resources, and cultivating fodder varieties with lower water requirements such as fodder sorghum. CD farmers also highly invest in livestock infrastructure, e.g. water troughs and storage tanks, chaff cutters, and cattle sheds. They are less dependent on middlemen as they have access to town and city markets.

4. Discussion

4.1 Climate change vulnerability, farming strategies, and HH resilience connect

The frequently cited definition of vulnerability is the degree to which a system is susceptible to and is unable to cope with the adverse effects of climate change (Adger, 2006). In this study, we found that farmers from different farming systems faced differential vulnerability owing to differences in perceptions of climate change exposure, experienced sensitivity, and coping or adaptation strategies (Amamou et al., 2018; Mubiru et al., 2018). HHs in all three farming systems reported a change in maximum temperature, delayed onset of monsoon, and dry spells due to higher intensity of the exposure, but while CWL farmers highlighted the impact of erratic rainfall, warmer winters, and high-intensity rainfall events, CSR, and CD farmers rather underscored reduced precipitation as the prime climate risk. The difference in perceptions between farming systems was highly linked to their contrasting farming focus and related sensitivity. For example, CWL farmers mainly depended on crop farming; hence, their production was highly sensitive to events such as erratic rainfall, warmer winters, and high-intensity rainfall events. CSR and CD farming systems, on the other hand, relied more on livestock and consequently were less sensitive to the weather events mentioned by the CWL HHs. However, CSR and CD farming systems needed good overall precipitation to ensure adequate grazing and water resources for their livestock.

The study also revealed that decision-making in farming and the choice of a certain farm strategy is a complex process. Factors such as differential sensitivity to climate change, access to livelihood capitals, and market forces like distinctive market prices between cash and food crops or demand for certain animal products all influenced how HHs of different systems chose their farming strategies (Singh et al., 2016; Li et al., 2016; Tripathi and Mishra, 2017; Amamou et al., 2018; Mubiru et al., 2018). Though exposure to climate change was felt by HHs in the region the study showed that the vulnerability of HHs mainly depended on the lack of certain HH livelihood capitals which were provided by ongoing national-level programs. The main capitals were the availability of water resources, ownership of livestock, access to grazing lands (CPRs and post-harvest croplands), adequate financial capital both in the form of investment flow and subsidies, higher education, and knowledge of sustainable agricultural practices.

The CWL HHs had no or limited access to all these essential capitals and hence showed the highest vulnerability. To cope, they chose to grow high-value cash crops over food crops in small landholdings. The lack of CPRs inhibited them to keep livestock; hence, they depended on inorganic inputs, off-farm jobs, or sold assets for survival. Low income prevented them from leasing lands and water resources. Finally, low education levels limited their networking abilities for accessing suitable subsidies or finances, further limiting their adaptation capacity. In all, the strategies opted for helped them to cope and meet their immediate needs but reduced their long-term resilience.

The CD HHs had access to all critical capitals mentioned above. However, the high human capital, i.e. relatively high level of education and extensive network contacts enabled them to get the necessary finance, subsidies, and relevant knowledge. Possessing high human capital facilitated the HHs to engage in more sustainable farming strategies such as the adoption of water-efficient systems, use of climate information services, shift to alternative crop varieties that used less water, improved livestock, animal healthcare, and improved feed management (Table 5). These strategies helped CD HHs to adapt and prosper in the short term. However, there exists a long-term risk of the borewells becoming defunct as water is a non-renewable resource.

The CSR HHs presented a different story as they belonged to a specific category (*Gollas)*, with a long history and strong identity as traditional livestock keepers. This identity, traditional knowledge, and high appreciation of livestock farming made them opt for different farming strategies compared to CWL and CD HHs. They chose to invest in livestock health, selected cash crops that provided crop residues, and leased grazing areas and borewells instead of digging new ones. These strategies made them less sensitive to climate change exposure and other non-climatic stressors in the region and seemed an effective long-term adaptation strategy.

From the social perspective, the SCs and HHs with small farms were the most vulnerable as they had the lowest access to capitals. Their presence was also highest in the CWL system which is the most vulnerable among all three farming systems (Table 2). Further, the STs (*Banjaras*) and the BCs (*Gollas*) had a high human capital related to livestock farming, which made them less vulnerable. Ethnic identity and traditional knowledge played a key role for HH resilience for both these groups (Kuchimanchi et. al.,2019). For the STs it helped access necessary capitals and attain better social status in comparison to the SCs. The BCs (*Gollas*) however, were far more resilient as they seemed to just modify their farm strategies while keeping their original occupation, unlike the STs who transitioned from nomadic pastoralists to settled dairy farmers.

Concerning gender, while both men and women had similar perceptions of climate change exposure, they were impacted differently due to their gender-specific farm and domestic responsibilities (Morchain et al., 2015; Rao et al., 2019). We found existing difficulties women face in farming are compounded by climate exposure. First, the loss of income and increased indebtedness due to the impacts of climate change on farm production drive men to migrate for work opportunities. This undermines the well-being of women in various ways (Rao et al., 2019) and leads to the feminization of farm work (Vepa 2005; Pattnaik et al., 2017). Longer working hours under maximum daytime temperatures are likely to translate into more heat-related health implications for women. Similarly, decreasing availability and loss of vegetation in CPRs, coupled with reduced crop residues have higher implications for women, since prolonged grazing hours interfere with domestic responsibilities while social norms prevent them to invest in fodder or leasing land. Lastly, though WSHGs created opportunities for livelihood diversification, climate change impacts on farm production (Table 5) increase the risk of loan repayment, especially for poor HHs. These factors together.

We thus conclude that the resilience of HHs in the study region depended on the concomitant availability of several livelihood capitals. We found that human capital, in the form of higher education levels and networking abilities helped CD HHs to articulate their adaptation pathways. Traditional knowledge and culture played a critical role in defining the adaptation strategy for the BC and ST HHs in the CSR and CD systems respectively and is possibly the reason why these castes had different responses to similar climate exposure (Crane, 2010; Adger et al., 2012). We therefore infer that farming strategies, livelihood capitals, and culture mutually influence each other, leading to specific development paths and climate change resilience for the HHs in these three farming systems (Figure 2).

4.2 Development policies in India drive farming strategies of rural HHs

India's policies have a long-term perspective on climate change adaptation, and the state and district-level programs aligned under these policies could positively influence availability and access to livelihood capitals in the form of schemes, subsidies, or development projects at various aggregation levels. However, several gaps exist. For example, in the study region, we find various development programs (see section 3.2) and market forces that continue to promote green and white revolution practices. These drive agricultural transitions towards highly water-intensive production systems, despite the projected negative climate change impacts for semi-arid regions (see sections 3.3.1 & 3.3.2). The CD system is a classic example of how an outcome of livelihood strategies promoted by development programs increases HHs' vulnerability to climate change exposure, as this farming system is highly sensitive to water and fodder shortages and increasing temperatures (Seo and Mendelsohn, 2007; Thornton et al., 2009; Porter et al., 2014; Rojas-Downing et al., 2017). The presence of such water-intensive farming systems, particularly in dryland regions, poses a risk as it can cause marginalization of many HHs over time due to groundwater depletion (Sishodia et. al., 2016; Shulkla et al., 2019). Furthermore, certain measures of development programs, e.g. conversion of wastelands into croplands,

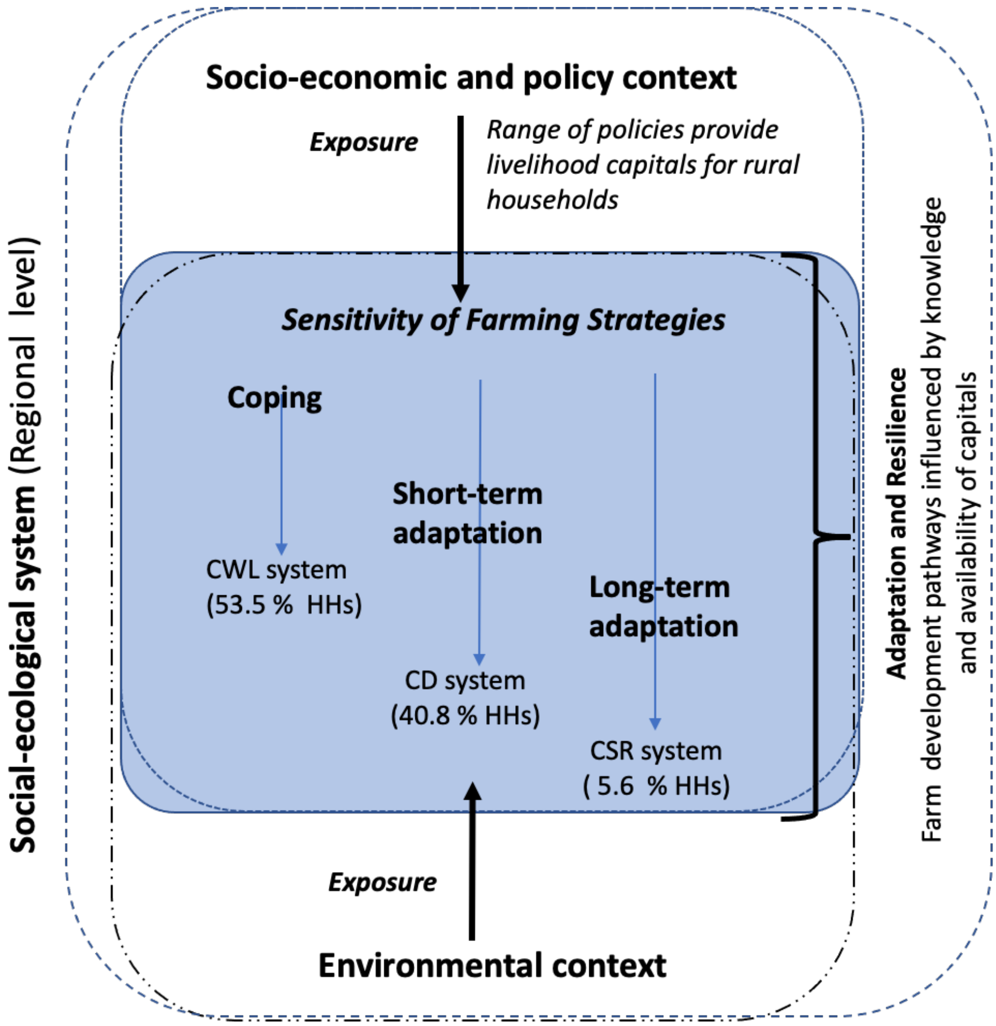

Figure 2: Components of a social-ecological system that influence farm development pathways, adaptation, and resilience

reduce CPRs and change land-use patterns, impacting the scope for small ruminant production in the future. Although traditional livestock keepers continue to adapt to such changes, climate exposures in the region exacerbate the existing problems in terms of further loss in vegetation cover in CPRs. Such long-term impacts are often not realized by ongoing state development programs and work out to be counterproductive to national climate change policy ambitions (Dubash and Jogesh, 2014; Adam, 2015; Gajjar et al., 2019; Singh et al., 2019b).

Hence, we highlight that ongoing state-level development programs need re-evaluation not only in the light of climate-related sensitivities faced by rural HHs, but also regarding the economic and ecological sustainability of current farming systems. Similarly, further research will be required to predict farm development pathways and their short-, medium-, and long-term impacts, as dryland regions are already bio-physically vulnerable ecosystems (Singh, et al., 2019a).

4.3 Research to improve climate change interventions and sustainability of farm development pathways

Substantial research efforts and development approaches have been undertaken to support climate change adaptation but with limited impact. Wise et al. (2014) attributed this to the lack of a broader understanding of ''adaptation pathways.'' Hence, in this study, we combined quantitative and qualitative research methods to get in-depth insights into adaptation pathways for informed policymaking. The use of mixed methods research provided perspectives on how development policies and programs stimulated or constrained farm development pathways, indicating varying short-, medium-, and long-term impacts. Quantitative research gives insight into the relative importance of phenomena, while qualitative research helps to identify the reasons behind a phenomenon for example farm strategies can be explained by the actual farm situation, while qualitative inquiry indicated the identity and aspirations of a farmer (Crane et al., 2008). Thus, mixed research methods enabled us to get a more holistic perspective on how certain trends evolve and why. We, therefore, recommend using mixed methods to understand the contextual nature of adaptation and help fine-tune adaptation policy and execution at the local level.

5. Conclusion

The present study aimed to enhance our understanding of the mutually influencing farming strategies, farm development pathways, and associated climate change vulnerability of three smallholder farming systems in the study region, namely, (i) crop without livestock (CWL), (ii) crop with small ruminants (CSR), and (iii) crop with dairy (CD) systems. The mixed methods research enabled us to understand the contextual nature of HH-level adaptation. The study shows that HHs belonging to different farming systems face differential vulnerability due to variations in perceptions of and sensitivity to climate change exposures and access to livelihood capitals. The CWL HHs system were highly vulnerable to increased maximum temperature and erratic rainfall. These factors affected crop farming and hindered their ability to take up wage work for long hours. However, HHs in the CD and CSR systems were more vulnerable to the overall precipitation reduction as it affected grazing possibilities and water resources for their livestock.

Though HHs in the region felt climate exposure, we found that market forces for cash crops and specific animal products and the accessibility of livelihood capitals provided by development programs highly influenced farming strategies. Consequently, HHs of different farming systems followed different development pathways and had different levels of climate change resilience. Among the three farming systems, the CWL system HHs had the least access to all livelihood capitals and showed the highest vulnerability. Their farming strategies only enabled to cope, meeting immediate needs at the expense of long-term resilience. In the CD system, HHs had access to all critical capitals, allowing them to opt for more sustainable farming strategies. However, these farming strategies will only last if HHs can benefit from their boreholes, extracting non-renewable water resources; hence the adaptation is not sustainable in the long run. The CSR HHs belonged to a specific ethnic group. This identity and traditional knowledge made them opt for low-risk farming strategies, leasing lands and water resources for a modified small ruminant production, and supporting long-term adaptation.

From the social group perspective, we found the HHs belonging to the SC group and those with small farms were mainly present in the CWL system and most vulnerable. The ethnic identity and traditional knowledge played a vital role in selecting farming strategies and adaptation pathways for the ST – *Banjaras* and BC – *Gollas*. In terms of gender, we found that men and women have similar perceptions of exposure but are impacted differently. Climate change tends to expose women more to exiting issues from transition and feminization of agriculture, while social norms prevent them from applying critical adaptation strategies.

Lastly, the case study showed that despite the integrated climate change policy at the national level, state-level development programs show a misalignment, focusing more on agricultural intensification than climate change adaptation. This situation stimulates farming strategies that are lucrative in the short term but endanger farming system resilience in the long term. Therefore, we recommend policymakers to give high priority to climate smart development, in close attunement of state development programs, and science-based evaluations of these programs if they aim to achieve economic development and climate change adaptation objectives in dryland regions. In the future, contextual studies that bring in more understanding of entwined farming development pathways of various dryland farming systems are warranted.

Chapter 6

General Discussion

1. Introduction

India has witnessed widespread agricultural transitions in recent decades, including the dryland regions (Ehrlich and Pingle, 2008; Amjath-Babu and Kaechele, 2015). Improved agrarian production owing to technological and infrastructural developments has helped alleviate poverty and achieve food self-sufficiency (Fan et al., 2000; FAO, 2018, Government of India, 2019). However, depleting soil fertility, diminishing groundwater, and the growing vulnerability of farmers to climate risks are persistent concerns (CRIDA, 2011). These impacts are likely to be amplified in the dryland regions of India due to its inherent biophysical vulnerability.

In this context, this thesis explores the transitions in farming systems in a dryland region in the southern state of Telangana, India, along with the subsequent risks and impacts of agricultural transitions on smallholder livelihoods and the local environment. Specifically, this thesis gains insight into the characteristics of the transitions from 1997 to 2015, the economic performance of emergent farming systems, and the impact of these systems on water resource availability in the region and their vulnerability to climate change.

This chapter first presents the main findings of the research (Figure 1),

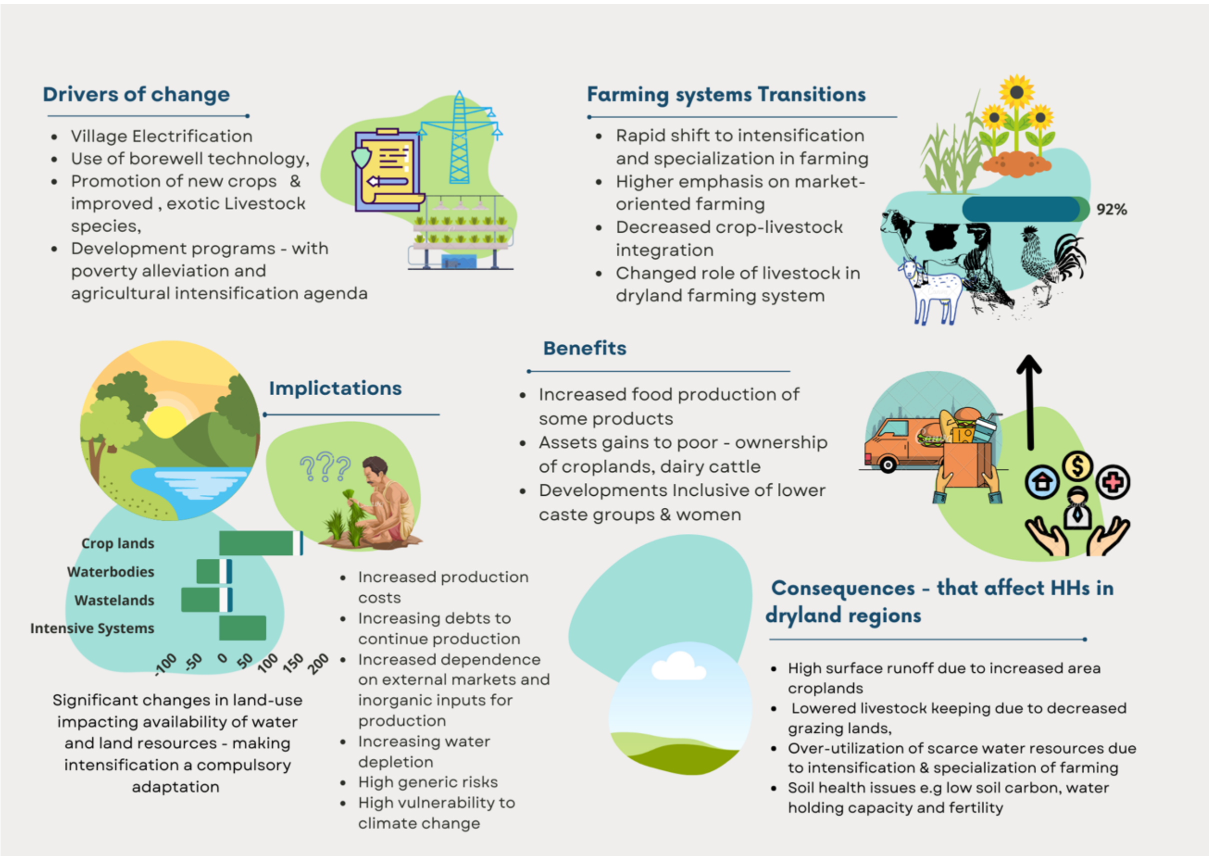

Figure 1: Transitions in farming systems – Drivers, Implications, and Consequences

followed by a discussion of the benefits and caveats of the methodologies followed Then, the implications of agricultural transitions in drylands are addressed. Finally, possibilities for sustainable intensification in such areas are explored.

2. Main findings of the research

2.1 Transitions in farming systems

Chapter 2 shows that at the regional level, the traditional subsistence mixed farming systems transitioned rapidly into intensive and specialized systems with high market orientation. The foremost drivers of these rapid changes were technological interventions, integrated development programs, proximity to a growing metropolitan city, and increasing market demand for certain agricultural products.

The transitions caused an extensive land-use change, where cropland increased by 45% and wastelands and natural surface water bodies reduced by 75% (**chapter 2, Table 3**). The transitions also triggered significant changes in land, water, and labour availability due to intensive market-oriented and water-demanding crop–livestock production. The transition process was inclusive and progressive for lower caste groups; for women the impact was dual.

The main inference of **chapter 2** is that benefits aside, transitions into more intensive and specialized forms of agriculture have also contributed to the scarcity of natural resources, marginalization of many HHs, and an increased burden on women in agriculture.

2.2 Current farming systems: characteristics and economic performance

Chapter 3 explores the impact of transitions in farming systems by characterizing the new farming systems and assessing their economic performance. Five farming systems were identified in the region, namely, crop without livestock (CWL), crop with dairy (CD), crop with small ruminants (CSR), landless with livestock (LWL), and crop with diverse livestock (CWDL) systems. Of these, the CWL, CD, and CSR systems were variants of specialized, intensive, and market-oriented farming. They comprised of 92% of the HHs in the region and provided a consistent income from agriculture. The LWL and CWDL systems were variants of subsistence farming.

The CD system had the highest revenues. The high production costs, however, offset the gross margins earned and sometimes led to negative gross margins. The CWL system had the lowest gross margin due to high production costs of cash crop cultivation and market price fluctuations. The CSR system showed the best economic performance. This was attributed to low production costs, high commodity prices, and market demand. HHs in the CWL and CD systems also had the highest credit and debt levels.

Overall, this chapter endorses, that intensification or specialization of farming in environmentally constrained regions does not always result in higher economic performance. Moreover, different farming systems perform differently where the CWL systems are at high risk due to low opportunities for diversification. The CD system showed the least consistent economic performance despite the specialization and consistent income. Meanwhile, the CSR system showed the highest economic performance as it adapted best to circumstances.

2.3 Intensive farming systems, water use, and dryland environments

In **chapter 4**, I analysed the impact of the three main intensive farming systems—CWL, CD, and CSR—on water resource availability at a watershed level. The CD system used the highest quantity of water, followed by the CSR and CWL systems. The CWL and CD systems comprised 86% of the HHs, making these two systems the prominent water users. Overutilization of water resources was evident due to the deficit in the watershed's water budget. This water overutilization and groundwater depletion is a fallout of the cultivation of water-demanding non-dryland crops, increased specialization of farming systems, and current agricultural practices. The main implication of this chapter is that current intensive farming systems and practices exceed the biophysical capacity of watersheds for long-term sustainability. Hence, farming systems need to be tune with the water resource–carrying capacity of the region.

2.4 Vulnerability, farming strategies, and farm development pathways of smallholders

Finally, in **chapter** 5, I analysed the farm strategies and farm development pathways of the three intensive farming systems to understand their vulnerability to climate change. We found that HHs in different farming systems faced differential vulnerability. This variation was due to differences in perceptions of climate change exposure in the region and differential access to the five livelihood capitals[1] (DFID, 1999). Although HHs in the region felt climate exposure, their farming strategies were influenced by access to and availability of livelihood capitals and market forces for certain agricultural produce.

Consequently, HHs of different farming systems followed different development pathways and had different levels of climate change vulnerability. The CWL system HHs had the least access to all livelihood capitals. This led them to choose farm strategies that only helped in meeting immediate needs, rendering them

[1] *Sustainable Livelihoods Framework* (DFID, 1999) advocates that HH-level livelihood objectives and strategies are shaped by how people use their asset base. The framework identifies five core asset categories or types of livelihood capitals, i.e. natural capital physical capital, financial capital, social capital, and human capital

the most vulnerable. The CD system HHs, despite having access to all critical livelihood capitals, opted for a few sustainable farming strategies (e.g. water-efficient technologies). However, these strategies supported only short-term adaptation, as these HHs depended on dwindling groundwater resources for production and viability. Meanwhile, CSR system HHs, despite having limited access to livelihood capitals, showed long-term adaptation, attributable to traditional knowledge linked to their ethnic identity. The small farmer category and the Scheduled caste (SC) groups were the most vulnerable. Contrastingly, caste groups with a strong ethnic identity[2] and traditional knowledge were most resilient. The effects of transitions and the feminization of agriculture exposed women more than men to climate change impacts.

In summary, farmer decision-making and development pathways are complex and driven by available livelihood capitals. Despite the presence of an integrated climate change policy continued to focus on economic development endangers the resilience of farming systems to climate change, particularly in dryland regions.

3. Methodology

In India, the social diversity in terms of social groups (caste) and farming system typologies is diverse. How these factors interact and affect the natural resource base is therefore complex. Hence, in this research, I chose to use a watershed as the unit of analysis as it makes an ideal social–ecological entity to study the various facets of agricultural transitions.

The watershed and its natural resources comprise the ecological components providing ecosystem services to the social component, i.e. rural populations and their farming systems (Wani et al., 2008; Reddy and Syme, 2019). Two watersheds were selected for the study, covering 27814 ha, 6572 HHs, and seven villages. From these seven villages, 17164 ha and 3006 HHs were chosen as representative samples to conduct the research.

As the social–ecological interactions within a watershed, given the sizable region and a large sample of HHs, can be complex, the reliance on a single method was insufficient. Hence, as a first step, a phenomenological study approach was adopted to make a deep dive into the region to describe, analyse, and understand the system. Subsequently, in all chapters, a combination of qualitative, quantitative, secondary data sources (e.g. government statistics), and geographic information systems (GIS) (when needed, e.g. in **chapter 2**) was used to triangulate results to

[2] In the study region, two distinct ethnic groups were present: the *Banjara*, categorised as Scheduled tribes, and the *Gollas*, categorised as backward class communities. Both these groups have a strong history of livestock keeping

obtain a larger and more consistent picture (Tamou, 2017). While quantitative research revealed the relative importance of the phenomena, qualitative research helped identify the reasons behind the phenomena. For example, the quantitative survey identified different farming systems or farm strategies adopted by HHs. Simultaneously, the qualitative inquiry indicated the identity, aspirations, and course of decision-making within farming HHs in the region (Crane et al., 2008). The use of a combination of methods allowed for a better understanding of agriculture transitions and their impacts. The approach provided a holistic perspective on how specific trends evolve. It also provided insights into the contextual nature of farming system development pathways and adaptation to climate change at a local level.

However, the choice of methodologies had a few caveats. The first concerns the focused group discussions (FGDs). I opted for a heterogeneous group of participants (i.e. both genders, different caste groups, ages, farm types, and landholding sizes) instead of a homogenous group approach. The inclusion of different groups and both genders in each FGD was intended to capture the nuances and divergent views of groups in the region and discuss potential discrepancies on the spot (Engel and Salomon, 1997; Hekkert and Negro, 2009). Heterogeneous FGDs, however, may entail the risk of certain groups (e.g. forward casts, wealthy, elderly or male participants) dominating the discussion. Hence, in this case, the use of an experienced facilitator helped avoid this and enabled the participation of all groups and members present. Despite the diverse participants, the uniformity in the transitions and adaptation strategies described across the groups was perplexing (**chapters 2 and 4**). This situation showed that the social diversity in the FGDs did not play a major role in identifying the expected nuanced narratives across groups. This could be attributed to the progression and development across India, which may have reduced caste hierarchy and related aspects in more developed states, like Telangana. The generalised economic drivers and the homogeneity in people's aspirations (regardless of the status) may also explain why the transitions described were uniform, as described by Matthei and Smith (2008) and Butler et al., (2014). However, in the case of women, a homogenous women-only FGD was conducted. This seemed necessary as the socio-cultural barriers in India inhibit women from openly voicing their opinion. A separate FGD helped capture their personal perceptions in-depth, understand how agricultural transitions impacted them and brought out how different their perceptions are from men.

Other aspects that may have caused biases in this research were the large sample size and the closeness of the study region to the city. While having a large sample size allows better extrapolation/prediction of certain parameters like transitions characteristic, farm development pathways, and statistical accuracy, there were limitations. Data collection on parameters such as labour, the contribution of financial systems, and the valuation of fixed assets in production costs were limited and could not be researched in-depth. Nonetheless, the longitudinal study with a sample of 75 HHs provided good opportunities to gain better insights.

The proximity of the study region to Hyderabad, Telangana's capital and one of the fastest-growing metropolitan cities, could have influenced the pace of transitions. Hence, I tried to include data from various sources for triangulating trends, to understand if the transition process was similar at state and national levels. Although similar trends were found across India, recent and reliable data on farming systems in India were limited. Therefore, generic insights into transitions across India have not been obtained yet.

Despite the various complexities in agriculture discussed above, the research findings have clarified how transitioning to intensive and specialized farming impacts smallholder livelihoods, livestock rearing, and the environment, particularly in biophysically constrained regions. This approach is therefore applicable across India's dryland regions, as well as other Asian and African countries where development policies are steering similar agricultural transitions.

4. The process and impacts of agricultural transitions, livelihoods, and drylands

4.1 The process

The transitions in farming systems from 1997 to 2015 in the region happened rapidly, surpassing social and cultural diversity in the Indian agricultural context. These transitions caused significant regional changes in the availability of land, water, and labour. These changes pushed HHs to intensify production. Therefore, the transitions were completely unidirectional in terms of becoming intensive and specialized with high market orientation. Currently, 92% of the HHs were variants of intensive systems, compared to traditional mixed farming systems in the past (see **chapter 2**). HHs without agricultural activities or following traditional subsistence (mixed) farming were fewer than 10% in the region. This shows that once the transition process gained momentum, farmers had to either join in or step out of agriculture (Dorward et al., 2009; Reardon et al., 2019).

A deeper analysis in **chapter 2** revealed that several concurrent drivers led the transitions in this region. Technological interventions such as village electrification and borewell technologies facilitated water-intensive crop and livestock production (Tian et al., 2014). Integrated development programs (e.g. watershed development) hastened transitions in farming systems by introducing agricultural intensification technologies. The availability of water due to watershed development measures in dryland regions encouraged smallholders to adopt new technologies and diversify faster (van Ginkel et al., 2013). Additionally, the increased market demand for specific crops and livestock products (Behera et al., 2015; Gathorne-Hardy, 2016) increased specialization in farming. Lastly, Hyderabad, the fastest-growing metro city in India, is a major market for the study region. While population growth itself is an important reason for the increased food demand the income growth of the urban population also influences food consumption patterns (Oosting et al., 2014; Kumar et al., 2017; Van der Lee et al., 2018; Reardon et al., 2019).

Besides the drivers identified in this study, other factors that might have played a significant role in causing the transitions include: the influence of external policy situations, reception of remittances, or differences in education and knowledge gains between castes or gender (Thompson et al., 2007; Reardon et al., 2019). While I discuss some of these aspects in the sections below, the scope for further research on these aspects remains.

4.2 Transitions towards intensive and specialized farming – mixed outcomes

The agricultural transitions in the study region resulted in a mixture of outcomes. Although regional agrarian production increased, the economic benefits were limited and came at the cost of the environment, while the social impact was two-fold.

4.2.1 Economic impact

The farming systems transitions in the region caused extensive land-use changes that favoured the expansion of croplands. Croplands increased at the expense of wastelands used for livestock grazing. This led to an overall reduction in livestock rearing by 48% of HHs in the region (**chapter 2**). While decreased livestock rearing by HHs *per se* is not a problem, it is a valid concern in dry regions, which are plagued by frequent droughts in conjunction with high temperatures (i.e. up to 45 °C) for 2-3 months a year. Such conditions limit biomass productivity and agronomic production (Srinivasrao et al., 2013). In such circumstances, the absence of livestock means a loss of a critical buffer for HHs in drought or dry spells, when crop production is unpredictable (Thornton, 2010; Herrero et al., 2013). Reduced livestock keeping also translates into decreased dietary diversity during lean periods (Fraval et al., 2020).

The increased availability of croplands hastened the transition to intensive and specialized farming as it facilitated the adoption of intensive agricultural practices. This resulted in the emergence of new farming systems. However, these intensive systems showed low economic performance, increased risks, and decreased flexibility to cope with disturbances and shocks (**chapters 3 and 5**). A situation like this arises because intensification and specialization reduce the circularity in farming that safeguards communities from risks inherent to dryland environments (FAO, 2008; Koohafkan and Steward, 2008). For example, reduced agricultural circularity breaks traditional production chains, barter systems, and other benefits that grazing systems provide to keep drylands resilient (FAO, 2008; IIED, 2010; Hodges, 2014; Notenbaert et al., 2012). Further, the increased market demand for certain livestock products, e.g. milk, reduced the production of other livestock products that otherwise brought additional income. This reduced the diversity within farming systems and eroded local animal genetic diversity, increasing the dependence on external markets for inputs and ultimately, raising production costs. Those who could not continue agriculture resorted to non-farm employment which was limited and led to income losses (**chapters 2 and 3**). Such trends have been reported in the literature on agricultural transitions in India, Asia, and Africa (Puskur et al., 2004; Jayne et al., 2014; van Ginkel et al., 2013; Oosting et al., 2014; Gathorne-Hardy, 2016).

Signs of a 'poverty trap' (Tittonell and Giller, 2013) were evident in the region. High production costs led to high levels of debt, as the current systems were not economically viable (**chapter 3**). Further, land in dryland regions is not as productive as lands in sub-humid and humid regions. Therefore, shrinking landholdings due to property division among siblings or urbanisation (**chapter 2**) will reduce economic viability further in the future. Shiferaw et al. (2008), Taylor (2013), and Ramprasad (2019) have emphasized that such factors tend to become intertwined with HH farming strategies to sustain intensive farming in dryland regions, eventually leading to vulnerability to climate change (**chapter 5**).

4.2.2 Environmental impact

Transitions in agriculture can give rise to environmental issues (e.g. overexploitation of natural resources) and social issues (e.g. farmer dependency on external inputs and marginalization of communities) (Lebacq et al., 2013; Clay et al., 2020). The study region, an already water-scarce region, also witnessed depleted ground and surface water availability. Borewell depths dropped from pre-2010 levels of 18–30 m to 180–250 m. The water budget of the study watershed showed a deficit of −3.78 Mm3/y (**chapter 4**). These findings align with the Central Ground Water Board's report (2019) that the region moved from a semi-critical to critical status between 2013 and 2017.

The groundwater depletion caused by the over-utilization of water resources driven by the cultivation of non-dryland crops, increased farm intensification and specialization, and farm management practices of the current systems (**chapter 4**). The dominance of croplands in the area (**chapter 2**) further aggravated the situation due to the low natural vegetation cover on these lands (Thomas and Duraisamy, 2019; Duraisamy et al., 2020). Together, these factors could have contributed to most HHs limiting crop production to one season per year as a coping mechanism (**chapter 4**). Batchelor et al., (2003), Joshi et al., (2004b), Sharma et al., (2005), Bouma and Scott (2006), Shiferaw et al., (2008), Reddy et al., (2007), and Calder et al., (2008) also report similar findings of water over-utilization in dryland regions across India. These insights assert that dryland watersheds have ecological limits, and production in these regions should be determined by the water resource–carrying capacity of the region. Otherwise, the risk of increasing desertification looms large, as reported in other dryland regions of the world (United Nations, 2011; IPCC, 2019).

4.2.3 Social impact

The social impact of the transitions was two-fold. There were notable positive changes in the convoluted social hierarchical (caste) system. Lower caste groups progressed by moving up the livestock ladder (Udo et al., 2011), gaining assets, and stepping out of caste-based occupations (**chapter 5**). Although Forward Castes (FCs) continued to dominate the agricultural setting, as, in the past, exceptions were found. For instance, in some cases, Scheduled Tribes (STs) had land and herd sizes as large as those of the FCs (**chapter 2**). Importantly, all caste groups were present in all farming systems and owned land (**chapter 5**). These developments in lower caste groups can be attributed to several government-sponsored schemes (Reddy et al., 2016) specifically designed for their upliftment (Government of India, 2008). We also found that the STs and Backward Castes (BCs) showed the lowest vulnerability to climate change compared to all other caste groups (**chapter 5**). The low vulnerability is due to their high human capital in livestock farming, originating from their traditional knowledge linked to their ethnic[3] groups. This traditional knowledge helped STs access necessary livelihood capitals and attain better social status than the SCs. However, the BCs (*Gollas*) were most resilient; their traditional and tacit knowledge assisted in retaining their original occupation while transforming it into a modernized sheep rearing system. Conversely, the STs transitioned from nomadic pastoralists to settled dairy farmers.

On the other hand, however, the majority of the HHs, i.e. the CWL and CD systems, showed high to medium vulnerability to climate change, with reduced long-term resilience (**chapter 5**). In the case of the CWL system, for instance, HHs had no or limited access to essential livelihood capitals, e.g. grazing lands, livestock ownership, and water resources. Therefore, their farm strategies were limited to meeting daily needs and were risky, e.g. cultivating high-value cash crops over food crops in small landholdings, high dependence on inorganic inputs, off-farm jobs, or selling assets for survival. Diminishing common property resources, low HH labour,

[3] In the region, the BCs are a traditional livestock-keeping community called the '*Gollas*', while the STs are the '*Banjaras*', who were nomadic pastoralists in the past but have now adopted sedentary agriculture

and less income prevented them from keeping livestock—a critical safety net for poor HHs in dry regions. Low levels of education limited their networking abilities for accessing suitable subsidies or finances. For the CD system, in turn, HHs had access to all essential livelihood capitals, which helped choose a few sustainable strategies (e.g. drip irrigation). Nonetheless, their adaptation was short-term as they were highly dependent on water, a scarce resource.

In the case of women, the transitions in farming systems increased their access to technologies, information, and livestock resources. However, on the flip side, their workloads increased, because women are the primary labour force in agriculture in India (Vepa, 2005; van Ginkel et al., 2013; Pattnaik, et al., 2017). A general reduction in women's small livestock and poultry rearing was observed due to increased workloads, depriving them of financial and nutritional security (Conroy et al., 2005; Chatterjee and Rajkumar, 2015). Women had similar perceptions of exposure as men but were impacted differently due to their gender-specific farm and domestic responsibilities (Morchain et al., 2015; Rao et al., 2019). Further, we found that climate change tends to expose women more than men due to existing issues from transitions in farming systems and feminization of agriculture (Vepa, 2005; Pattnaik et al., 2017). The social norms prevent them from applying critical adaptation strategies. Together, these factors undermine the well-being of women in various ways (Rao et al., 2019), now and in the future.

Reardon and Timmer (2014) display how the presence of five 'interlinked transformations' namely intensification of farm technology, agri-food system transformation, rural factor market transformation, urbanisation, and diet change, can transform the economy of a region as a whole rather than in parts or independently. Although my study looks at fragmented parts of these interlinkages, the findings can be related to the theory they present. Therefore, as Reardon and Timmer (2014) point out sustainable intensification of agricultural production and food security depend on the interdependence of several factors within these 'interlinked transformations'. Hence agricultural production strategies must encompass all these aspects in this era of large urban markets and rural–urban linkages because farm intensification and commercialization are closely interconnected.

5. Policies drive smallholder farming system pathways

The results in this study lead to a critical inference that prevailing policies tend to determine smallholder farming system pathways. For instance, India's socio-economic development priorities for its vast and growing population and political dynamics tend to influence policy formulation (United Nations, 2019; Brown et al., 2021), and central government budgets. These budget provisions steer development programs and subsidies that promote agricultural intensification and other technologies to increase food production and nutritional security. A recent example is the 2021 central government budget, which proposes doubling India's annual milk processing capacity from 53.5 million tonnes (mt) to 108 mt by 2025 (Government of India, 2020-21) despite the projections of growing land degradation, water scarcity, and climate risks across the country's dryland regions (World Bank, 2012; Kumar and Kumar, 2013; IPCC, 2019). Such provisions exemplify how development programs like Watershed Development Programs (WDPs[4]) continue to promote agricultural intensification for agricultural and livelihood enhancement. Moreover, such interventions become counterproductive to the water and land restoration measures of WDPs the effects of which we see in **chapters 3 & 4** (i.e. overuse of scarce water resources, groundwater depletion, and others). Studies by Batchelor et al., (2003); Joshi et al., (2004b); Sharma et al., (2005); and Bouma and Scott, (2006) also report such findings across India.

Furthermore, the need to address multiple objectives to sustain India's rapid economic growth also gives naissance to policy incoherence. This reflects in the form of a lack of integrated action between policies and the resultant conflicting or unintended outcomes (Weitz et al., 2017; Muscat et al., 2021). For instance, policies supporting smallholder agrarian production, such as power subsidies and irrigation infrastructure (Shiferaw et al., 2008; Fishman et al., 2014; Sishodia et al., 2016), accelerate excessive groundwater pumping and irreversible land-use change in dry regions (Thomas and Duraisamy, 2019; Duraisamy et al., 2020) when coupled with agricultural intensification, and market demand. Hence, while a taking multiple objective approaches—which is often the case for developing countries—coordinated action is critical to avoid unintended social and ecological consequences.

Similar policy incoherence is evident in India's recent climate change policy. Although India has a clear climate change mandate at the central level, the state-level interventions still aim at livelihood and regional economic development and not climate change adaptation. This incoherence has resulted in unintended consequences at the local level such as the increased vulnerability of rural HHs to climate change (Gajjar et al., 2019; Singh et al., 2019b). This is because critical livelihood capitals (e.g. availability of water resources, ownership of livestock, and access to common property resources (CPRs; see **chapter 5**), that HHs must possess to stay resilient in the region have been altered, overused, or inadequate as agricultural transitions evolved in the region (**chapters 2–4**). Therefore, most of the

[4] WDPs are India's most extensive development program for drylands focused on improving rural livelihoods through enhancing agricultural productivity by increasing the availability of surface and groundwater for agricultural production

HHs in the area (mainly the CWL and CD systems) showed higher vulnerability to climate change.

Along the same lines, agricultural credit and financial systems also play a crucial role in agricultural development, particularly in developing countries (Benton et al., 2021; Bernards, 2022). As food production at a higher level is moulded by the need to produce cheaper food economic structures are often tuned to produce food at lower costs (Benton et al., 2021). For this to happen, agricultural credit and financial systems are made available for certain types of farming, often fostering intensification, marketization, and commercialization of agriculture (Bernards, 2022; Ripoll-Bosch and Schoenmaker, 2021). In dryland regions, this could be detrimental in the long run as these ecosystems are fragile and resource-constrained.

6. Developed and developing countries: differences and similarities in agricultural development pathways

The findings of this thesis are not isolated phenomena. Rapid and region-wide transitions from subsistence farming to market-oriented farming are reported across drylands in Asia (Green and Vokes, 1997; Reardon et al., 2019; Vishwanathan et al., 2021; Zao et al., 2022), Latin America (Gazzano et al., 2019), and Africa (Senbet and Simbanegavi, 2017; Van der Lee et al., 2018; Jayne et al., 2019). These studies show similar transition pathways and both beneficial and undesirable impacts, comparable to those found in this thesis. Location-specific insights notwithstanding, all studies show that policies for food production, proximity to cities, urban population growth, and market demand for certain products incentivize farmers to intensify production and adopt modern inputs. Although the intensification of farming systems increased the overall production in the region, this was accompanied by higher competition for and scarcity of natural resources, generating dissimilar benefits across households.

Such transitions are not just limited to developing countries but have also occurred in industrialized countries. In fact, this continues to happen. Take for instance the agricultural intensification and specialization in the European Union (EU) since WWII (Ripoll-Bosch and Schoenmaker, 2021). This intensification was aimed at increasing food production based on the economic model of high outputs at low margins per unit product. Therefore, the EU's agricultural production is among the most intensive globally, yet with a large environmental burden, such as high GHG emissions (EuroStat, 2017), soil acidification, eutrophication, and reduced agro-biodiversity (Bais-Moleman et al., 2019). From a social perspective, people employed in agriculture dropped by 30% in the last 15 years, and the declining trend continues (Schuh et al., 2019). Despite well-developed technological and infrastructural frameworks, sustainable farming in the EU remains challenging in the face of barriers to production, distribution, and consumption (Bais-Moleman et al., 2019; Baldock and Buckwell, 2021).

Such insights from developed countries indicate that critical action is needed for sustainable development in dryland regions. The urgency for sustainable intensification pathways in these regions is most pressing as they largely fall in developing countries that are undergoing rapid agricultural transitions. Further, these regions are highly sensitive to environmental changes compared to other agro-climatic regions. Hence, the absence of favourable natural resources will impact the economic development and stability of agrarian-based livelihoods (Rao, 2008; Moni, 2009; Wale and Dejenie, 2013; Robinson et al., 2015; Lu et al., 2018) of a large proportion of the poor population rapidly. While current agricultural systems may already be under pressure, climate change prediction adds another layer of adversity in the form of erratic precipitation, increasing aridity, droughts, and floods (IPCC, 2018). Hence, continued transitions toward the intensification of land and water use will only exacerbate land degradation, water scarcity, and food insecurity in drylands (IPCC, 2019). Prăvălie et al. (2019) state that except for Europe and South America, all continents have experienced a net expansion of arid environments in the recent climate database, and Asia is in the lead with the maximum increase in dryland areas.

7. Sustainable agricultural intensification and dryland environments: the way forward

In line with the above, current policies may need to be overhauled in terms of context, foresight, and coherence (Dubash and Jogesh, 2014; Adam, 2015; Gajjar et al., 2019; Muscat et al., 2022). In addition, integral approaches that go beyond policy may be needed to tackle current environmental and social issues (Reardon and Timmer, 2014; Bais-Moleman et al., 2019; Baldock and Buckwell, 2021; Runhaar, 2021). Therefore, in this section, I deliberate on the possible directions toward sustainable agricultural intensification, synthesized through discussions with communities, the longitudinal study with farming HHs, secondary data, and published literature.

7.1 A plethora of information: the need for a change in outlook

It is clear that dryland watersheds have limits to the services they can provide, with implications for food production and livelihoods. From a livestock perspective **chapters 3 and 4** elucidate how sedentarisation of livestock in dryland regions (e.g. the CD system) may be unsustainable and can lead to land degradation and excessive water use. Ekaya (2005) and Brikse et al. (2015) reported similar findings in South Asia and Africa. Therefore, maximizing provisioning services, like food production, through agricultural intensification, occurs at the cost of other regulatory, supporting, and cultural ecosystem services that are unique to dryland environments (MEA, 2005; Wale and Dejenie, 2013; Costanza et al., 2017; Lu et al., 2018). Therefore, food production strategies in dryland regions need to be carefully weighed.

Studies advocating the importance of ecosystem services state that appropriate agricultural practices can ameliorate the disservices from intensive agriculture (Dale and Polasky, 2006; Power, 2010; Bowman and Zilberman, 2013). A strong knowledge base about the evolution of farming systems in dryland regions, benefits of mobile livestock farming systems, native livestock breeds and ecological processes, and traditional knowledge systems of pastoralists exists (Marty, 2005; Thornton et al., 2007; Hodges et al., 2014; Nori et al., 2008; IIED, 2010; Köhler-Rollefson and Mathias, 2010; Notenbaert et al., 2012; Hodges, 2014; Tamou et al., 2019; FAO, 2021). There is also considerable literature on the biophysical attributes of dryland ecosystems (Gajbhiye and Mandal, 1983; Millennium Ecosystem Assessment, 2005; UNEP, 2011). Despite such a plethora of research, only some of which is cited here, limited uptake or mainstreaming of interventions in policies and practice are observed.

This knowledge could be used to develop sustainable food production strategies for resource-constrained regions. Launching studies on how pastoral and agro-pastoral systems have evolved and are surviving across Asia and Africa could also yield valuable solutions. For example, this study showcases how the CSR system, a mobile production system, has transformed into an intensive modernized system by traditional livestock keepers themselves. This system also demonstrated the best economic performance and displayed a high capacity to adapt according to the dynamic context of the region. HHs in this system also exhibited the highest resilience to adapt to climate change compared to the other two emergent systems (CWL and CD systems). This ability stemmed from the traditional knowledge they had (**chapters 2, 3, & 5**). Accordingly, supporting existing pastoral systems would be fortuitous as they are economically and ecologically more compatible with dryland regions (Nori et al., 2008; IIED, 2010; Krätli and Schareika, 2010; Notenbaert et al., 2012; Kauffman et al., 2019). Alternatively, where not possible, strategies that reduce the over-utilization of water resources could be promoted to make intensification more sustainable**.** Some examples could be the promotion of circularity in agricultural systems (Muscat et al., 2021; Oosting et al., 2022); dryland suitable feed, and animal management options (Descheemaeker et al., 2009, Kebebe et al., 2015, Tamou et al., 2018a, b); accentuate agronomic practices that maximize soil carbon levels (Plaza-Bonilla et al., 2015; Giller et al., 2021), and higher area-wide integration between farmers (Kumar and Singh, 2008; Udo et al., 2011; Oosting et al., 2014; Ripoll-Bosch et al., 2014; Kannan, 2015; Van der Lee et al., 2018) **(see chapters 3 & 4).**

Although a range of solutions exists, numerous barriers inhibit the adoption of more ecologically sustainable food systems (this study and Runhaar, 2017, 2021; Gliessman, 2020). Therefore, I discuss a few structural changes that could address existing challenges and bring about a paradigm shift.

7.2 Strengthening the science-policy interface

Like other developing countries, India has several rural development initiatives supported by bilateral partnerships to alleviate poverty through improved agrarian livelihoods. Although the operational framework of these programs is well-intended, knowledge gaps and implementation issues result in counterproductive outcomes. Findings in **chapters 3–5** indicate that these problems could be overcome by strengthening the science-policy interface. For instance, in **chapter 4,** the water budget at the watershed level showed a high surface runoff in the region. However, despite the deployment of watershed management measures in the region the runoff remains considerably high. This is likely caused by climate change, as changes in climate influences the timing and magnitude of runoff (Marshall and Randhir, 2008). A prudent science–policy interface would integrate appropriate run-off prevention measures such as suitable agronomic practices (e.g. cover crops, mulching) and facilitate climate science-based alterations in the watershed engineering structures (e.g. check dams, gully plugs, percolation tanks, contour trenches, etc.) to mitigate the consequences seen in this study. Similarly, in **chapter 5**, policy analysis revealed that climate-smart agricultural production within existing development programs is limited or absent. This gap has long been cited as a critical barrier in India and many developing countries (Tanner et al.,2006; Sietz et al., 2011; Chowdhury et al., 2021; Lee et al., 2022). A robust science-policy interface for development planning is essential to facilitate knowledge diffusion and empower government institutions. In addition, more interdisciplinary research on dryland ecosystems is warranted. Future research should assess the relative feasibility of varied farming systems in dryland conditions and the associated socio-economic impact of agricultural intensification, e.g. indebtedness and access to credit, HH dietary diversity, or gender implications.

Another aspect a good science-policy interface should enable is improving monitoring and evaluation mechanisms for the continuous process of improvement. In **chapter 5** we found the absence of a feedback mechanism on how policies or program interventions respond in the short, medium, and long term. That resulted in unintended consequences. In the same chapter, we realised that the use of mixed methods and science-based evaluations in implementation (i.e. monitoring and evaluation) can help understand the contextual nature of development pathways. Therefore, strengthening the current monitoring and evaluation mechanism of development programs with mixed methods research will facilitate the progression of appropriate farming pathways; maintain policy coherence; fine-tune implementation gaps, thereby mitigating counter-productive outcomes.

Lastly, developing countries typically follow developed countries in adopting the path of agricultural intensification to increase productivity. It may be imperative to shift gears and learn from the failures the EU is facing due to high levels of agricultural intensification. As agriculture in developing countries has not yet transitioned fully, and elements of circularity, diversity, and traditional knowledge still exist - strong science–policy interface through bilateral partnerships could help optimize existing production systems and support the dissemination of appropriate knowledge.

7.3 Fostering partnerships to support sustainable farm development pathways

A shift to sustainable agriculture takes time and varies under different agroecological and socioeconomic conditions. Therefore, incentives and benefits through appropriate public-private partnerships are vital to buffer this gap period. A few options emerging from this research are (1) new policies that incentivize the uptake of farm strategies for water conservation (Fishman et al., 2015; Shao and Chen, 2022; WRI, 2021), (2) the introduction of region-specific agricultural commodity pricing, (3) favourable financial and credit systems promoting the adoption of suitable agroecological crop-livestock production (Harding et al., 2021; Ripoll-Bosch and Schoenmaker, 2021), (4) new investments in the development of low-cost technologies (e.g. bio-fertilizers and pesticides), and (5) the repurposing of subsidies to boost the shift and uptake of sustainable practices (Bowman and Zilberman, 2013; WRI, 2022).

These measures are critical because, as described by Runhaar (2021), path dependencies and 'lock-ins' in industrial food systems, which are growing globally, limit farmers' own choices on what to produce, how, and for whom. This is triggered by the ongoing pressure to intensify, specialise and scale-up, coupled with the export orientation of many food systems. Though industrial systems are limited in India, similar lock-ins were observed in **chapters 4 and 5** where farming strategies and development pathways of rural HHs are strongly driven by policies and programs driving agricultural intensification. Therefore along with a science–policy interface, public–private partnerships also needs to be fostered to make the shift smooth and viable.

7.4 Mainstreaming community-led resource management

With a strong science-policy interface and public-private partnerships, the anticipated change would not be possible without community stakeholdership, a cornerstone for sustainable development. Institutional capacity-building at the village level needs to be further strengthened with new information and approaches beyond the dynamics of intensification and specialization in farming systems (Jayne et al., 2014; Amjath-Babu and Kaechele, 2015; Thornton and Herrero, 2015). Some such initiatives, e.g. community engagement approaches and tools,[5] though well demonstrated by civil society organizations, tend to remain pigeon-holed. However, when backed by science-based evaluations, these approaches can avoid conflicting interests while implementing technological development (Nedumaran et al., 2014). Such tools can generate knowledge about complex social–ecological processes, facilitate an interactive learning space, and promote local innovations by tapping local or traditional knowledge systems to improve the management of dryland environments (Tamou et al., 2018).

In addition to this, Nandi and Nedumaran (2021) highlighted the importance of the aspirations of farming communities in shaping their activities and investments. The rapid and unidirectional transitions (**chapter 2**) and farm development pathways (**chapter 5**) seen in this study align with the need to consider communities. Nandi and Nedumaran (2021) further state that intergenerational aspirations and corresponding investment plans in agriculture are usually at odds, calling for changes in these barriers. This could be another potential area to bring about a necessary shift to sustainable agriculture as high aspirational populations visualize and engage in forward-looking behaviour (Dalton et al. 2016; Kosec and Mo, 2017).

In this chapter, I raise a range of issues that calls for a paradigm shift at multiple levels, i.e. an enhanced science-policy interface, a strengthened public-private partnership, and the involvement of local communities. While this is challenging, alternative methodologies and ways of working, such as “co-creation,” can help address the described gaps. Co-creation is a popular and widely spreading concept globally (Osborne et al., 2016; Brandsen et al., 2018; Leino and Puumala, 2021). Co-creation allows breaking down hierarchies between concerned stakeholders, such as local governments, the business sector, universities, and communities. It moves away from the classical dichotomy of a top-down or bottom-up process and strives for a multi-directional approach to problem-solving (Leino

[5] http://www.fao.org/climate-smart-agriculture-sourcebook/enabling-frameworks/module-c1-capacity-development/c1-case-studies/case-study-c111-the-andhra-pradesh-farmer-managed-groundwater-systems-apfamgs-project/en/
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and Puumala, 2021). In developing countries, that are predominantly dryland regions, co-creation may fit well as it is an adaptive and emergent process (Keeys and Huemann,2017). While it brings together stakeholders, e.g. local governments, researchers, or business sectors, it most importantly will get on board local/ethnic communities who have a distinct presence in these regions. Incorporation of their traditional knowledge, views, and aspirations may ideally lead to the design of more inclusive and sustainable futures.

Summary

Despite three decades of agricultural transitions in India, studies on the consequences of such transitions at the regional and farming system level remain limited. Furthermore, the impacts of agricultural intensification are likely to be more acute in dryland states of India, due to its inherent biophysical vulnerability. Therefore, this study was conducted in a region in the southern state of Telangana; one of the seven dryland states of the country. The aim of this thesis was to "understand transitions in farming systems and gain insights into the sustainability implications they have at a farm and watershed level in a dryland context"**.** Within this background, this thesis gains insight into the characteristics of the transitions, the economic performance of emergent farming systems, the impact of these systems on water resource availability in the region, and their vulnerability to climate change.

To address the research objectives, mixed methods—both qualitative and quantitative approaches—were employed to gather and analyse the information. Broadly, the methods employed included household surveys, focused group discussions (FGDs), timeline mapping exercises, a longitudinal survey, secondary data collection, and Geographic Information Systems (GIS) methods with ground-truthing to confirm land use land cover changes, and statistical analyses as appropriate. As this research is embedded in social–ecological systems theory, a watershed was taken as the unit of analysis. Watersheds can be considered an ideal social–ecological entity to study the various facets of agricultural transitions. This is because, the watershed and its natural resources comprise the ecological components providing ecosystem services to the social component, i.e., rural populations and their farming systems. The two study watersheds cover 27,814 ha, 6,572 HHs across seven villages in a region in Telangana. From this, 17,164 ha and 3,006 HHs were selected as a representative sample to conduct the research.

Chapter 2 showed that a concomitant presence of various drivers such as technological interventions, development programs with integrated approaches, proximity to a growing metropolitan city, and increasing market demand for certain agricultural products led to rapid changes in farming systems in the region. While agricultural production increased at a regional level, significant changes in land, water, and labor availability also occurred. The transitions favored an increase in croplands by 45% at the cost of wastelands and natural surface water bodies that decreased by 75%. Water-demanding cash and commercial food crops replaced traditional dryland crops. The function of livestock in farming changed from a multi-purpose role (i.e. drought power, provision of fuel, manure, additional income from animal by-products and animal source foods) to a market-oriented food production role. Thus, the transitions in farming systems were completely unidirectional,

becoming intensive and specialized with high market orientation. The transitions also surpassed the social and cultural diversity in the region, as it was inclusive of lower caste groups. For women, both benefits (e.g. opportunity to engage in livestock production, ownership of livestock, access to finance and technologies) and drawbacks (e.g. increased workload) were found. The generalised opportunities to engage in farming and intensify production indicate that once the transition process gained momentum, farmers had to either join in or step out of agriculture. Therefore, the study confirms that, aside from increasing overall food production, transitions into more intensive and specialized forms of agriculture also trigger the scarcity of natural resources, and therefore marginalization of HHs in the long term.

In **chapter 3,** the characterization of the new farming systems and assessing their economic performance revealed the presence of five farming systems namely: crop without livestock (CWL; 48% HHs), crop with dairy (CD; 38% HHs), crop with small ruminants (CSR; 6% HHs), landless with livestock (LWL; 6.8% HHs), and crop with diverse livestock (CWDL; 0.8 %) systems. Of the five, the CWL, CD, and CSR systems were variants of specialized, intensive, and market-oriented farming, while the LWL and CWDL systems were variants of subsistence farming. The traditional mixed farming systems had completely disappeared as the CWDL system was the only remnant. Among these, only three systems (i.e., CWL, CD, and CSR) provided a consistent income from agriculture and comprised 92% of the HHs. The economic performance study showed that the CD system had the highest revenues. However, the high production costs, offset the gross margins earned and sometimes led to negative gross margins. The CWL system had the lowest gross margin due to high production costs of cash crop cultivation and market price fluctuations of the products. The CSR system showed the best economic performance due to its high adaptability to changing circumstances. This was attributed to low production costs, high commodity prices, and market demand. Further, most of the HHs (86% of the sample) fell in the CWL and CD systems that had an average daily per capita income below the World Bank extreme-poverty threshold (2018) of USD 1.9 day/person. These systems also showed high credit and debt levels, along with increased risks and decreased flexibility to cope with disturbances and shocks. The factors causing this situation were: low opportunities for diversification, reduced crop-livestock diversity within farming systems, erosion of local animal genetic diversity, and diminishing grazing resources. These factors, in turn, increased the dependence on external inputs and the market, which ultimately raised production costs and associated risks. Overall, findings validate that intensification or specialization of farming in dryland regions may not always result in higher economic performance.

In **chapter 4**, the impact of the three dominant farming systems (i.e. CWL, CD, and CSR) on water resource availability at a watershed level was assessed. The coupled interaction of the water use in different farming systems and the water budget at different scales (i.e., farming system, village, or watershed), provided an enhanced understanding of the water availability and use in the region. The highest quantity of water was used by the CD system (8,122 m^3/HH/y), followed by the CSR (2,869 m^3/HH/y) and CWL (1,833 m^3/HH/y). The CWL and CD systems (86% HHs) were the most prominent water users. Signs of overutilization of water resources were evident as the watershed's water budget showed a deficit of −3.78 Mm3/y. The water overutilization can be explained by the cultivation of water-demanding non-dryland crops, increased specialization of farming systems, and current agricultural practices.

The over-utilization of water resources may have resulted in water scarcity, as borewell depths had increased, their functionality across the year reduced, and considerable variation in borewell pump discharge (2,000-5,227 l/h) was found. This is probably why most HHs (i.e., the CD and CWL systems) were found to have limited crop production to one season per year as a coping strategy. Thus, the main conclusion of this chapter is that current intensive farming systems are not in tune with the water resource–carrying capacity of the region.

Finally, in **chapter 5**, a vulnerability assessment of the three dominant farming systems (i.e. CWL, CD, and CSR) was undertaken. HHs in different farming systems faced differential vulnerability which was due to differences in perceptions of climate change exposure and variance in access to the five livelihood capitals. Despite climate exposure in the region, HH farming strategies were influenced by access to and availability of the five livelihood capitals[1] and market forces for certain agricultural produce. Consequently, HHs of different farming systems followed different development pathways and had different levels of climate change vulnerability. Of the three systems, the CWL HHs had the least access to all livelihood capitals. This led them to choose farm strategies that only helped in meeting immediate needs, rendering them the most vulnerable. HHs in the CD system, despite having access to all critical livelihood capitals, opted for a few sustainable farming strategies (e.g. water-efficient technologies). However, these strategies supported only short-term adaption, as they depended on dwindling groundwater resources for production. Meanwhile, CSR HHs, despite having limited access to livelihood capitals, showed long-term adaptation, attributable to traditional knowledge linked to their ethnic identity. Among the social groups, the small farmer category, the SCs caste group, and women were the most vulnerable. In contrast,

[1]*Sustainable Livelihoods Framework* (DFID,1999) advocates that HH-level livelihood strategies are shaped by how people use their asset base. The framework identifies five core asset categories or types of livelihood capitals, i.e. natural capital, physical capital, financial capital, social capital, and human capital.

caste groups with a strong ethnic identity[2] and traditional knowledge showed the highest resilience. In the case of women, the effects of transitions and the feminization of agriculture exposed them more to climate change impacts when compared to men. At the policy level, despite the presence of an integrated climate change policy, the continued focus on economic development endangers the resilience of farming systems to climate change, particularly in dryland regions.

All the studies in this thesis point out that transitions to more intensive and specialized forms of agriculture also trigger the scarcity of natural resources and marginalization of HHs. This is likely more rapid in dryland regions owing to the inherent biophysical limitations. Literature shows similar findings in other regions across India. Similar results are also reported in Asian and African countries, which are predominantly drylands. Moreover, such transitions are not just limited to developing countries but have also occurred in industrialized countries (and continue to happen). Despite well-developed technological and infrastructural frameworks, sustainable farming in the EU, for instance, is also challenging due to existing barriers to changing current production, distribution, and consumption. Such insights from other developing, but also developed countries, indicate that critical action is needed for sustainable development of farming systems, and particularly in dryland regions due to its casuistry. The urgency for sustainable intensification pathways in these regions is most pressing as they largely fall in developing countries, host largely poor populations, and are undergoing rapid agricultural transitions.

Therefore, while current policies may need to be overhauled, there is a need for integral approaches that go beyond policy to tackle current environmental and social challenges. This research, synthesized through studies at various levels, including engagement with local communities, suggests directions towards sustainable agricultural intensification. First, there is a need to change the outlook when developing sustainable food production strategies in resource-constrained regions. This is because, despite a plethora of research on drylands and their associated aspects, it is seldom used in policy formulation or practice. Second, for a shift in paradigm, certain structural changes need to occur, such as strengthening the science-policy interface, fostering partnerships that support sustainable farm development pathways, and mainstreaming community-led resource management. For these to materialise "co-creation" of policies and programs for sustainable intensification of dryland regions is the need of the hour.

[2] In the study region, two distinct ethnic groups were present: the *Banjara*, categorised as Scheduled tribes, and the *Gollas*, categorised as backward class communities. Both these groups have a strong history of livestock keeping.

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My PhD journey has been a journey of a lifetime!

I say this as my first attempt to get enrolled was in the year 1998 immediately after the Master's program. Although efforts started back then, there were many challenges on the way, until I finally registered at Wageningen University and initiated work in 2014-15. Here is my story in brief, with sincere thanks to the many people who played a crucial role in helping me achieve my end goal.

My initial attempt to get enrolled into a PhD program was in 1998, but like every other Indian girl back then, I was expected to get married first. In fact, only a fraction of my female batchmates went beyond pursuing a Master's degree. The same year I did get married, and the wishful seed of wanting to pursue a PhD lay dormant for several years. I started work in the Development sector and worked under the broad umbrella of rural development. Over a period of time, the field of livestock development became the closest to my heart. As work progressed, I became more involved in this arena and at least had one livestock-related project in the larger portfolio of work. The seed (for higher studies) germinated in 2005, and I attempted to reapply for PhD registration. I looked for opportunities within India but did not find anything suitable to the topic I had in mind. *The seed, however, grew into a seedling via the sprinkling of knowledge I had gained.*

As the journey progressed, from writing concept notes to applying for scholarships, I met several people who assisted me in my trials and tribulations, some of whom I sincerely acknowledge as I would not have come this far without them. Topping the list is Dr. Mohamed Osman, Principal Scientist at the Central Institute for Dryland Agriculture, India. He guided me on a fodder development project for small ruminants in 2006. Due to my immense interest in livestock-based livelihoods and a keen inclination towards pursuing a PhD, he introduced me to the Late Dr. Michael Blümmel, a renowned scientist at the International Livestock Research Institute. Since 2006 Dr. Blümmel was a strong pillar of support to me, till he left India in 2014. He introduced me to international PhD opportunities, taught me how to develop research proposals, provided me with the necessary contacts to apply for such projects, and was always there to be a local supervisor if needed. It deeply pains me that he is no more, now when I have finally graduated.

Despite so much perseverance and mentoring support, a successful PhD registration still eluded me. However, the efforts continued and between 2005 to 2014, there were dry spells, drought years, and some opportunities too! *The young seedling grew into a sturdy shrub, with a few strong branches, some feeble ones and several new shoots.*

The least I know was that some of the people I met and the events that unfolded would eventually help me towards the getting a PhD.

In India, during those days the livestock projects were mostly supported by Swiss foundations, and almost all specialists or capacity building experts were Dutch; so, my association started with them way back in 2004. Several foreign students would come to my workplace for their internships and whoever I worked with were always Dutch! One of them was Ms. Charlotte van der Tak. We continued to stay in touch and have been good friends since 2005. We made a wishful pact to meet up exactly 10 years from then in Europe. I had no inkling, whatsoever, that Charlotte would be the start point to my PhD journey 10 years later!

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"Only when the student is ready, the teacher appears" - a saying in Buddhism

Around 2010, through Dr. Blümmel, I met many others at ILRI and through Dr. Birgit Boogaard I met my supervisor, Prof. Dr. Simon Oosting, and Prof. Dr. Imke de Boer in

2011 virtually! Yet again, despite everything being in place in terms of support grant, supervisors, a research proposal, opportunities came and went with no luck. In 2013, all doors to financial aid closed permanently, as I wasn't eligible for any scholarships having crossed the age eligibility criterion. I seemed to have hit a dead end after all. It was indeed a dream unfulfilled, but importantly with no regrets.

Suddenly out of the blue, in 2014, thanks to Ilse, I got an opportunity to attend a meeting in Brussels. This one opportunity, the universe gifted, got me another chance to pursue my dream. From Brussels I travelled to Netherlands to meet Charlotte! I reached Europe a year earlier and we laughed at the pact we made almost a decade ago. I emailed Dr. Simon that I wanted to meet him, and Charlotte took me to Wageningen as she was an alumnus of that university. The purpose was just to meet Simon face to face and thank him for all the extended support; but things turned out quite unexpectedly. Simon shared that Wageningen University had made the rules more flexible for external PhD candidates and that I should not give up. He helped me work out a schedule around the finances I had. To say that I was in state of total disbelief, would be an understatement.

"The universe does conspire"

Although it appeared doable, being able to travel and stay in the Netherlands still seemed difficult. Yet again, Charlotte showed me the way forward and introduced me to her parents Vera and Johan, who stay in Bennekom. They hosted me for every trip to the Netherlands and if not for their love, care, and support none of this would have been possible. Another happy coincidence is that Vera and my mother are the same age and share the same birthday too!!! While getting a foreign PhD degree is a high in itself, I now have Dutch parents too. I am very grateful for their support.

While the three important men in my life; my father, my father-in-law and my husband offered to crowdfund my studies, I decided to take care of the finances myself. Finally in 2015 the actual work on the PhD started. I thank my former boss Dr. Marcella D'Souza at the Watershed Organization Trust for allowing me to do the thesis work alongside my job. This offered the much-needed flexibility I wanted. I thank Marcella for this considerate gesture. I thank my team back then namely Chennaiah, Srujan, Thirupati and Anil for working those extra hours on conducting household and longitudinal surveys. I also extend a very special thank you to Divya Nazareth, Sivaranjini Umapathi, Renie Thomas and Vijaysekaran Duraisamy for technical and moral support during my thesis work. I also thank Marije Wilting for conducting the survey for Chapter 5 which was a part of her internship here in India. Working with her was a treat as she saw things differently and her perceptions added value. Towards the last fag and most critical phase of the thesis work (post 2019) I thank Mr. Jagdeesh

Puppala, former Executive Director of Foundation for Ecological Security (FES) for providing me with a suitable work opportunity. A special mention to all my other colleagues at FES namely Rahul, Pratiti, Himani, and Mr. Sanjay Joshie, the current Executive Director, who gave me that much needed space and support to balance work and study. I thank each one of them whole heartedly.

A very special thanks goes to both my supervisors: Prof. Dr. Simon Oosting; I thank him for taking up this responsibility, believing that I could do it and handholding me till the very end. I find it hard to fathom that a person can trust and teach a foreign student, who has no financial aid and whom he hardly knew. A rare and admirable quality, which was the single biggest reason which kept the fire in my belly burning. I thank him for all his patience, repeatedly telling me not be an NGO activist while writing, working around my job schedule, and always clearing the muddle in my head – as I transitioned away from a practitioner way of thinking.

Next, I thank my co-supervisor Dr. Raimon Ripoll-Bosch. I'm immensely grateful for his supervision and support at the most critical time. Apart from work related to my thesis, I can't help but compliment him for being a very perceptive person and being able to council students through their journey, which often a supervisor may not do. Though I didn't know many a time how to express myself he always knew exactly what I needed to hear and pitched in at the right time. He was always cheerful and easy to approach, undoubtedly the best supervisor one can have.

Dr. Annemarie van Paassen gets the next heartfelt thanks. It was a pleasure working with her as she guided me through my thesis chapter 5. As I was using mixed methods, I had a tough time merging the social methods with natural science ones. Discussions with her were very helpful as she pointed towards the right kind of literature that helped connect the two in the right way. I thoroughly enjoyed working with her and thank her for supervising me. It's surprising, but the fifth chapter was the one that got published first!

I thank Prof. Dr. Imke de Boer, who despite her very busy schedule, always made time to interact and supervise when I was in the Netherlands. She was warm and encouraging and told me that if I ever had difficulty in finding accommodation, I could fall back on her. This was indeed very reassuring. I also take this opportunity to thank Dr. Eddie Bokkers, for helping me out with the MOOC course and that finally helped completing my hanging TSP.

Though my stints at the Animal Production Systems (APS) Group were very short, colleagues at APS made me feel very much a part of the Department. I thank Abigail, Windi, Titis, Ollie, Akke, Aart, Sally, Brain, Evelyn, Alejandro, Margret, Corina, Iris, Simon, Theo and Laura. But a special thanks goes to Abigail and Windi, among all.

Among everyone at APS, Ms. Lia Verheijen and Ms. Fokje Steenstra have been my pillars of support. Lia made sure I had a desk in her room, never once complained that the room felt like a “furnace” as I couldn’t tolerate the cold. She made sure I got up from my desk occasionally. Window shopping, coffee, and pastry breaks with her were the most enjoyable and relaxing. Fokje, on the other hand played several roles, she was my go-to person from day one. While it was professional at first it has grown into a friendship that will last forever. She took time to call me very regularly, which really helped particularly during the Covid period. What I appreciate the most is how she designed my thesis, and which is in a watercolor paint style as that’s one of my hobbies. A huge thank you from the bottom of my heart to both of you for being always there for me.

Apart from this, a few associates namely Dr. Anjal Prakash, Dr. Chandni Singh and Dr. Sunaina Singh helped me cross many difficult terrains. A sincere thanks to them for their timely help, inputs and constant encouragement.

Right in the end, the biggest thank you is reserved for my husband Murali and daughter Aditi for putting up with me. The long absences from home both for work and studies, not being able to attend important family and personal events, and the list is never ending. A sincere thank you to my parents and my in-laws also, both of whom have been my biggest support always stepping in and managing things for me at home so I could focus on the goal I had set.

The tree has finally bloomed and is bearing fruit!

About the Author

Bhavana is a native of Hyderabad, the capital city of the southern state of Telangana, India. In 1998 she obtained her Master's degree in Agricultural Sciences from G.B. Pant University of Agriculture and Technology, India, subsequent to which she got into the development sector. As a development professional, Bhavana's core experience has been in the practice domain primarily in natural resources management. Although natural resources management encompasses a variety of disciplines, her core interests and experience lie in agricultural systems, livestock-based livelihoods, and climate change adaptation. Bhavana has a keen interest in strengthening the research and practice interface and conducting research for impact.

While pursuing her job in India, she enrolled as a part-time PhD student at the Animal Production Systems group at Wageningen University and has been conducting her research under the supervision of Prof. Simon. J. Oosting and Dr. Raimon Ripoll-Bosch. Her thesis explores the impact of agricultural transitions on smallholder livelihoods and on the environment within the context of dryland ecosystems.

She is currently working as a Sr. Research Fellow with the Foundation for Ecological Security (FES), an India-based non-governmental organization that works towards maintaining ecological security, as it is the foundation of sustainable and equitable development.

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Education Certificate

Completed training and supervision plan*

**One ECTS credit equals a study load of approximately 28 hours*

The Basic Package	**Institute/Place**	**3 ECTS**
Course on Scientific Integrity	WIAS	2020
Course on Ethics and Animal sciences	WIAS	2020
Course on essential skills (Frank Little)	WIAS	2017

Disciplinary Competencies		**21 ECTS**
PhD proposal	WIAS	2015
Towards a bio-based society: from principles to practices	WIAS	2021
Sustainable Food Security - The value of systems thinking	WUR MOOC course	2021
Vulnerability and Risk assessment Tool	Oxfam & University of Botswana	2018
Modules on Sustainable Agriculture	The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)	2015
Modelling the Environment	Swiss Agency for Development and Cooperation & Watershed Organisation Trust	2013
Environmental Impact Assessment for Planning Ecologically Sustainable Livestock Production	Swiss Agency for Development and Cooperation – IC	2007
Rapid Appraisal of Agricultural Knowledge systems (RAAKS) at its application	ETC, Netherlands & Swiss Agency for Development and Cooperation	2005
Gender mainstreaming in NRM	Human Institutional Development Forum & Timbuktoo Collective	2002

Professional Competencies		**3 ECTS**
Techniques for Writing and Presenting a Scientific Paper	WUR	2017
Management Development Program	Indian Institute of Forest Management	2007

Presentation Skills		**4 ECTS**
Stakeholder Consultation: The future of India's Livestock Sector, Oral	New Delhi , India	2017
Adaptation Futures Conference, - Oral	Cape Town, South Africa	2018
WACASA presentation - Oral	WUR	2019
Presentation at India land and Development Conference - Oral	Land New Delhi	2019

Teaching Competencies		**2 ECTS**
MSc Thesis Supervision -1		2017

Education and Training Total		**33 ECTS**

Colophon

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