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Climatic Variations Influenced Distribution and Productivity of Different Agroforestry Systems in Rajasthan, India

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Abstract: Farmers of Rajasthan conserve and promote scattered trees and shrubs growing on farmlands to deal with climatic adversities. These woody perennials sustain livelihoods by providing economic, social, and environmental benefits. Tree-based farming systems were surveyed in all 10 agroclimatic zones (ACZs) of Rajasthan for screening best models and suggests for further improvement. Trees were assessed for density, and growth parameters in 0.5 ha plots, whereas agricultural crops yields were estimated in 1 m^2 plots laid at 1 m from tree trunk, canopy edge and 5 m away from trees canopy (control). There were 107 tree-crop combinations involving 14 trees and 21 crop species. *P. cineraria*-based systems were dominant in the arid western, whereas *A. nilotica* dominated in semi-arid to dry sub-humid regions. Average tree density was 11.7 trees ha^{-1} ranging from 3.3 tree ha^{-1} in ACZ-IIIb to 23.6 tree ha^{-1} in ACZ-IIa. *Senegalia senegal* showed highest (27.6 tree ha^{-1}) density. Height and canopy diameter were 11.73 m and 10.35 m respectively, in irrigated ACZ- IIIb and decreased to 6.53 m and 5.02 m in ACZ-IIb, respectively. Both height and density decreased with the decrease in rainfall from south-east to north-west. *D. sissoo* and *T. grandis* were taller, *S. oleoides* was thicker and *Z. mauritiana* was shorter and thinner than other species. Grain yields varied from 0.66 in ACZ-Ia to 1.85 Mg ha^{-1} in ACZ-IIIa, but exhibited low yield as compared to control. Crop yield reduced by 22.9-47.3% between ACZs, 20.3-56.5% between agroforestry systems, and 15.9-79.8% between intercrops highlighting the interactive effects of these components. *S. senegal, T. undulata, P. cineraria, Z. mauritiana, S. oleoides, V. tortilis* and *P. juliflora* based systems showed 29.1-54.9% low, whereas *V. nilotica*, *D. sissoo*, *A. indica*, *T. grandis* and *V. leucophloea* based systems showed 4.5-51.7% high yield over the state average. The yield of groundnut (IIIa), cotton (IVa), barley (IIIa), jowar (IVa), maize (IVa), paddy (V), pearl millet (IIIa) and wheat (V) with *A. nilotica* was above state average. Pearl millet and Isabgol were best suited with *P. cineraria* with least crop reduction in ACZs-Ia/IIa and IIb, whereas moong

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bean and maize were best with *V. nilotica* in ACZ-IIa and IVb respectively. Our findings indicate that tree integration on farmlands reduces crop yields, but the extent of yield reduction depends on suitability of tree-crop combinations in different agroclimatic zones, hence suitably be selected for enhanced production.

Key words: agroclimatic zones, agroforestry, climatic factors, crop production, dry land.

Intensive farming practices, overgrazing, deforestation, loss of biodiversity, and climatic changes coupled with soil erosion have led to severe land degradation and desertification (Leakey *et al*. 2005; Jinger *et al*., 2023). About 29.7% of the total geographical area of India including Rajasthan is degraded (SAC, 2021). Rajasthan has 20 million hectares of cultivated area, but 80% of this area is rainfed, where rainfall is highly erratic and unpredictable making agriculture a gamble (Malhotra *et al*., 1986). At the same time, Rajasthan supports about 5.6% human and 10.7% livestock population and constitutes 8.5% of total milk production in India (GoR, 2011; Soju and Meena, 2017). To cope up with climatic adversities, people of this region promoted and protected woody perennials on their farmlands since time immemorial (Harsh *et al*., 1992). Various agroforestry models the people of this region have adopted are agri-silviculture, agri-horticulture, and agri-horti-silvi systems depending upon the types of combination between tree, horticultural species, agricultural crops, and grasses (Khan and Tewari, 2009). The extent and distribution of these agroforestry systems depend upon topography, biophysical attributes, and socio-economic acceptance in the region (Tewari and Singh, 2006; Kumar *et al*., 2014; Singh, 2016).

Agroforestry helps in reducing soil erosion, improving air, water, and soil quality, carbon sequestration and conservation of biodiversity (Alavalapati *et al*., 2004; Jose, 2009; Bezu and Abera, 2021). By providing continuous supply of organic matter to the soil agroforestry increases beneficial soil micro- and macro-organisms, preserving water nutrient cycling and improving soil fertility (Tripathi *et al*., 2005; Barrios *et al.,* 2012; Glover *et al*., 2012; Cortez *et al*., 2014). Hence, agroforestry is an important tool to increase and sustain food production per unit area and has potential to ameliorate and mitigate the adverse effects of climate change and is increasingly seen as a promising approach to improve food security (Jama and Zeila, 2005; Bayala *et al*., 2012; Quandt *et al*., 2017). Net positive effects of interactions between woody and herbaceous components under long-term valuations highlight the importance of mixing trees and crops to reduce the gap between actual and potential yield through more efficient use of resources (Smethurst *et al.,* 2017). In Rajasthan, Khejri (*Prosopis cineraria*) is the most preferred multipurpose tree species covering more than 60% area under agroforestry due to its synergetic effect on crop yield (Singh and Rathod, 2016). Desi babul (*Vachellia nilotica*) is another multipurpose tree observed in integrated farming systems in semi-arid and sub-humid regions of the state. Among, agri-horti systems, Ber (*Ziziphus mauritiana*) is more compatible with leguminous crops in arid and semi-arid regions of Rajasthan (Singh *et al*., 2003; Tewari *et al*., 2007).

Although agro-forestry has potential benefits to the farmers, it is well recognized that tree components can negatively influence crop production and income, when trees and crops are not properly selected and managed. It is because of competitive interactions for above- (i.e., light) and below-ground resources (water and nutrients) between trees and the companion crops (Ong *et al*., 2004; Kuyah *et al*., 2016). Integrated tree component also reduces the land area available for crops and hence the net effect of agro-forestry on crop yields over time will depend on various attributes of the system and types of interactions between different components. Numerous results indicate that crop production decline by 15% to 90% at 1 m distance from trees depending upon the types of tree species under use (Puri *et al*., 1995; Kausik and Kumar, 2003; Kaushik *et al*., 2017; Singh, 2004; Singh *et al*., 2014; Tewari *et al*., 2014). For example, *Colophospermum mopane* tree competes with agricultural crops at the highest for soil resources followed by *Tecomela undulata*, *Hardwickia binata* and *Prosopis cineraria* (Singh, 2004; 2010). Tree species that have more lateral and few tap root systems influence crop yield the most (Toky and Bisht, 1992; Kahi *et al*., 2009; Singh *et al*., 2014).

This indicates that resource management in agroforestry systems potentially provides options for climate change adaptation and mitigation with simultaneous improvement in livelihoods by enhanced production of food, fodder, and firewood. This study was conducted to evaluate the effects of different tree species on the grain yield and total biological yield of associated agricultural crops either inside or outside of the tree canopy and compare with open field areas in different agroclimatic conditions of Rajasthan. This will help screen the best agroforestry system for a particular agroclimatic zone and recommendations for further replication.

Materials and Methods

Site description

Rajasthan is situated between 23° 30′ and 30° 11′ N latitudes and 69° 29′ and 78°17′ E longitudes in the north-western region of India. The western part is dry and less fertile and the south-western part is relatively wetter, hilly, and more fertile as compared to the other regions of the state. The state can be divided into four regions namely the desert in the west, barren hills, rocky/sandy plains in the northeast, the Aravali hills in the centre, extending from north to south, and south-eastern plateau. Rajasthan is also divided into four major agroclimatic zones viz. Arid, Semi-arid, Humid and Sub-humid covering 61%, 16%, 15%, and 8% areas of the state respectively (GOR, 2012). These zones are further delineated into 10 agroclimatic zones (Fig. 1). Rainfall, the most important factor limiting crop production, ranges between 150 mm in Jaisalmer to 1100 mm in Jhalawar district annually. About 70% of the total arable area of the state mainly depends on the kindness of the monsoon. As per the land use statistics, area coverage under Kharif crop

Fig. 1. Map showing agro-climatic zones in Rajasthan. Source: www.Krishi.Rajasthan.gov.in

is 164.41 lakhs ha during 2016-17 and 164.44 lakhs ha during 2017-18. Crop productions were 8.37% and 25.75% higher in 'Kharif' and 'Rabi' seasons of 2016-17 respectively, as compared to those in 2017-18.

Experimental design

This study was based on one-time field data collection through physical measurements and field observations on tree growth and crop yield from the existing traditional agroforestry systems. Multistage purposive randomized sampling technique was used to select the sample plots in 1-2 districts in each agroclimatic zone depending on the availability of the agroforestry systems. In each district, 3 to 6 farmers' lands distributed in different tehsils were selected randomly with a total of 87 farmer's lands. Sample plots of 0.5 ha area were laid out on the farmlands covering all ten agro-climatic zones distributed in 15 districts from June 2016 to March 2018.

Observations recording

All tree species were counted for species richness and trees >2.0 m tall or having >16 cm girth at breast height (gbh) were enumerated and measured for height, gbh, canopy diameter (two direction perpendiculars to each other) and canopy cover. A total of 659 individual trees of different species were measured. The relative basal cover of a species was calculated as the basal cover of a species divided by total basal cover of all the species multiplied by 100 and dominant tree species were identified on the basis of highest relative basal cover. For crop yield estimation, 1737 temporary plots of size 1 m × 1 m were laid out at three different distances from the tree trunk viz. 1 m distance from the tree trunk (under canopy zone), tree canopy edge, and 5 m away from the canopy edge of the selected tree as the control. Three replicate plots were laid on three different farmlands depending on the availability of the trees for each agroforestry system. Total dry matter, straw/husk and grain yield was recorded during 'Kharif' and 'Rabi' seasons, i.e. during October to November and March to April months in both 2016-17 and 2017-18 for each combination and presented as Mg ha^{-1}. Crop yield reduction or enhancement was calculated for the yield at 1 m distance from tree trunk and at the canopy edge in comparison of yields in control plots (considering 100% yield) and by using the following equation:

$$\text{Yield variations (\%)} = \frac{\text{(Crop yield in referred plot} - \text{Crop yield in control plots)}}{\text{Crop yield in control plots}} \times 100 \quad \ldots(1)$$

Statistical analysis

All data collected were subjected to analysis of variance using SPSS statistical package. Data on height, diameter at breast height (dbh), collar diameter and crown diameter of the tree, and crop yield etc., were analysed using two ways ANOVA. In this, type of tree species and distance from the tree trunks were the main factors. Pearson correlation coefficient was calculated for observing relationships between different variables.

Results

Tree-crop combinations

One hundred eleven tree-crop combinations were observed in the state those involved 21 dominant crops (both 'Kharif' and 'Rabi' seasons) and 14 silvicultural tree species listed in Table 1. Dominant crop was Bajra or pearlmillet (*Pennisetum glaucum*) followed by Guar (*Cyamopsis tetragonoloba*) and Moong bean (*Vigna radiata*) during 'Kharif' and Wheat (*Triticum aestivum*) followed by Mustard (*Brassica nigra*) in Rabi seasons.

Dominant trees of agroforestry systems: *Prosopis cineraria* was the prominent tree of the system in arid region, whereas *Vachellia nilotica* was prominent in semi-arid region of Rajasthan where agriculture is predominantly rainfed in kharif season. Other systems practiced in certain pockets of some agroclimatic zones were *Tecomella. undulata* (Rohida) in ACZs-Ia, IIa, IIb, *Dalbergia sissoo* (Shisham) in irrigated area of Ib and Ic zones, and *Ailanthus excelsa* (Ardu) in ACZs IIa, IIIa and IIIb (Table 1). Most dominant tree species with highest number of companion agricultural crops (15 crop species) was *V. nilotica* (Supplementary Table 1). It was followed by *P. cineraria* (8 species of agricultural crops), *Azadirachta indica* (Neem) and *D. sissoo* with 7 crop species each, and *T. undulata*, *V. leucophloea* and *V. tortilis* (6 each). Least number of agricultural crops was with *P. juliflora* and *Tectona grandis* (Teak or Sagaun), i.e. 2 crop species each.

Table 1. Diversity of agroforestry systems, associated trees and agricultural crop species recorded in different agroclimatic zones of Rajasthan

ACZ*	Dominant tree-based agroforestry	Associated tree species	Agricultural crops
Ia	*Azadirachta indica, Prosopis cineraria, P. juliflora, Salavadora oleoides, Senegalia senegal, Tecomella undulata, Vachellia tortilis* and *Zizyphus mauritiana*	*Ailanthus excelsa, A. indica, Capparis decidua, P. cineraria, P. juliflora, S. oleoides, S. senegal, T. undulata, V. nilotica, V. tortilis*, and *Z. mauritiana*	*Arachis hypogaea, Brassica nigra, Cuminum cyminum, Cyamopsis tetragonoloba, Eruca sativa, Hordeum vulgare, Pennisetum glaucum, Plantago ovata* and *Triticum aestivum*
Ib	*Dalbergia sissoo, V. nilotica*, and *V. tortilis*	*A. excelsa, A. indica, P. cineraria, C. decidua, D. sissoo, T. undulata, S. oleoides, V. leucophloea, V. nilotica, V. tortilis* and *Z. mauritiana*	*B. nigra, C. tetragonoloba, Gossypium hirsutum, Oryza sativa, T. aestivum*, and *Vigna radiata*
Ic	*D. sissoo, P. cineraria, T. undulata* and *Z. mauritiana*	*A. excelsa, A. indica, C. decidua, P. cineraria, S. oleoides, S. senegal, T. undulata V. nilotica, V. tortilis,* and *Z. mauritiana*	*A. hypogaea, C. tetragonoloba, P. glaucum, V. aconitifolia* and *V. radiata*
IIa	*Ailanthus excelsa, A. indica, P. cineraria, T. undulata* and *V. nilotica*	*A. excelsa, A. indica, C. decidua, D. sissoo, P. cineraria, S. oleoides S. senegal, V. luecophloea, V. nilotica, V. tortilis, T. undulata,* and *Z. mauritiana*	*C. tetetragonoloba, P. glaucum, V. radiata* and *V. unguiculata*
IIb	*A. indica, P. cineraria, S. oleoides, V. leucophloea, V. nilotica* var. *cupressiformis* and *Z. mauritiana*	*A. excelsa, A. indica, C. decidua, P. cineraria, P. juliflora S. oleoides, S. senegal, T. undulata, V. nilotica, V. tortilis,* and *Z. mauritiana*	*B. nigra, Cicer arietinum, H. vulgare, P. glaucum, P. ovata, Sorghum bicolor*, and *V. radiata*
IIIa	*A. excelsa, A. indica, V. nilotica,* and *V. nilotica* var. *cupressiformis*	*A. excelsa, A. indica, D. sissoo, P. cineraria, S. oleoides V. leucophloea, V. nilotica,* and *Z. mauritiana*	*A. hypogaea, C. tetragonoloba, C. arietinum, H. vulgare, P. glaucum* and *T. aestivum*
IIIb	*A. excelsa, A. indica* and *V. nilotica*	*A. excelsa A. indica, D. sissoo, P. cinerari,* and *V. leucophloea*	*B. nigra, P. glaucum* and T. aestivum
IVa	*V. leucophloea* and *V. nilotica*	*A. indica, P. cineraria, S. oleoides, V. nilotica, Z. mauritiana*	*G. hirsutum, Lens culinaris, S. vulgare, T. aestivum* and *Zea mays*
IVb	*A. indica, T. grandis* and *V. nilotica*	*A. excelsa, A. indica, D. sissoo, P. cineraria, V. leucophloea, V. nilotica*	*Glycine max, T. aestivum* and *Z. mays*
V	*V. nilotica*	*A. excelsa, A. indica, D. sissoo, P. cineraria,* and *V. leucophloea*	*C. sativum, G. max, O. sativa, T. aestivum* and *V. mungo*

*ACZ- agroclimatic zones; Ia- Arid North Western Sandy Plain; Ib- Irrigated North Western Plain; Ic- Hyper Arid Partial Irrigated Zone; IIa- Transitional Plain of Inland Drainage; IIb- Alluvial Plain of Luni Basin; IIIa- Semi-arid Eastern Plain; IIIb- Flood Prone Eastern Plain; Iva- Sub-humid Southern Plain and Aravallis; IVb- Humid Southern Plain; and V- Humid South Eastern Plain.

Ailanthus excelsa based system: *A. excelsa* is important trees of farmlands recorded in agroclimatic zones (ACZs) IIa, IIIa and IIIb. Other associated species were *P. cineraria* and *A. indica* as tree crop and pearl millet (*Pennisetum glaucum*), moong bean (*Vigna radiata*), cluster bean (*Cyamopsis tetragonoloba*), moth bean (*V. aconitifolia*) were the crops associated with this tree in zone IIa. In zones IIIa and IIIb, associated tree species were *P. cineraria, V. nilotica*, and *A. indica* and the intercrops were pearl millet, groundnut (*Arachis hypogaea*), moong bean, and cluster bean in 'Kharif', and wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), gram (*Cicer arietinum*), and mustard (*Brassica nigra*) in 'Rabi season'. This system provides multiple benefits in the form of fodder, timber, and foods.

Azadirchta indica based system: *A. indica* (Neem) based system was sampled in ACZs - Ia, IIa, IIb, IIIa, IIIb, and IVb (Table 1). Other tree species observed associated in this system were *P. cineraria, V. nilotica, A. excelsa, Z. mauritiana* (Ber) and *S. oleoides* (Meetha Jal). *P. cineraria, Z. mauritiana* and *S. oleoides* were associates in ACZ-Ia, where agriculture crops were pearl millet, moong bean, cluster bean, moth bean, wheat (*Triticum aestivum*), cumin (*Cuminum cyminum*) and mustard. *P. cineraria, V. nilotica* and *A. excelsa* were associated tree species in ACZ-IIa, whereas *P. cineraria, V. nilotica, Z. mauritiana* and *S. oleoides* were associates in ACZ-IIb. The intercrops were pearl millet, moong bean, cluster bean, moth bean and sesame (*Sesamum indicum*) in 'Kharif', and wheat, barley and Isabgol (*Plantago ovata*) in 'Rabi' season. Both tree associates and crop varied in different agroclimatic zones.

Dalbergia sissoo based system: *D. sissoo* based agroforestry system was sampled in ACZs-Ib and Ic, where adequate irrigation water is available. It is a fast growing, hardy, and important good quality timber species of deciduous behaviuor. The associated tree species were *P. cineraria, V. nilotica*, *A. indica* and *V. tortilis* and the intercrops were pearl millet, moong bean, cluster bean, cotton (*Gossypium hirsutum*), paddy (*Oryza sativa*) and groundnut in 'Kharif' season and wheat, mustard and gram in 'Rabi' season.

Prosopis cineraria-based system: *Prosopis cineraria*-based system was predominant in ACZs-Ia, Ic, IIa, and IIb (Table 1), though it was also observed in ACZs-Ib, IIIa and IIIb. It is an important multipurpose tree species and was found associated with other tree species like *T. undulata, S. senegal*, *V. tortilis*, *Z. mauritiana*, *S. oleoides*, *A. indica,* and *Capparis decidua* (Ker). The intercrops were bajra, moong bean, moth bean and cluster bean during 'Kharif' season and wheat, mustard, Cumin, and Isabgol during 'Rabi' season. Khejri was associated with different tree and crop species in different ACZs.

Prosopis juliflora- based system: *Prosopis juliflora*-based agroforestry system was significantly less and found only in ACZ-Ia covering Barmer and Jodhpur districts (Table 1). It is an aggressively colonizer and become menace if casually managed. Other tree species found in this system were *Prosopis cineraria, T. undulata, S. senegal*, *V. tortilis*, *S. oleoides* and *A. indica*. The intercrops found cultivated with this tree species were pearl millet and cluster bean during 'Kharif' season and wheat and mustard during 'Rabi season, i.e. under irrigation.

Salvadora oleoides- based system: *Salvadora oleoides,* also known as Meetha Jaal, was found in agricultural lands of Barmer and Pali districts covering ACZ-Ia and ACZ- IIb respectively (Table 1). It is an evergreen tree with a dense crown with numerous drooping branches. Other tree species found as associates in this system were *P. cineraria, T. undulata*, *A. indica, Z. mauritiana, P. juliflora* and *V. tortilis* Cultivated intercrops were pearl millet, and cluster bean during 'Kharif' season, and wheat, gram and Taramira (*Eruca sativa*) during 'Rabi' season.

Senegalia senegal based system: This system was studied in ACZs-Ia, though observed in other ACZs also (Table 1). Other tree species associated with *S. senegal* (Kumath) were *P. cineraria, T. undulata, Z. mauritiana* and *V. tortilis*. In this system, the intercrops were bajra, moong bean, cluster bean, moth bean and sesame during 'Kharif' season. Wheat, barley, cumin and Isabgol were cultivated during 'Rabi' season but only in ACZ-Ia. This system provides fuel, fodder, and seed for vegetable and gum enhancing livelihood in the region.

Tecomella undulata based system: *Tecomella undulata*-based system was observed mainly in ACZ-Ia, Ic and IIa confined to the western arid region (Table 1), though occurs in other areas also covering ACZs-I and II. Although varied between different ACZs, common associated tree species in this system were *P. cineraria, S. senegal, Z. mauritiana* and *Capparis decidua*. Different intercrops cultivated in this system were bajra, cluster bean, moong bean, moth bean and choula during 'Kharif' season and wheat, barley, cumin and Ishabgol during 'Rabi' season (only in zone Ia).

Tectona grandis based system: *T. grandis* (Teak) based system was observed in ACZ-IVb, where rainfall is relatively high. Teak is a tropical hardwood tree species, occurs in mixed deciduous forest and provides most valuable timber for wider uses (Table 1). This system had tree associates like *V. nilotica* and *A. indica*. Different agricultural crops found cultivated in association of this system were soybean (*Glycine max*), maize (*Zea mays*), and black gram (*V. mungo*) during 'Kharif' season and wheat and barley in 'Rabi' season.

Vachellia leucophloea based system: *Vachellia leucophloea* based system was dominant in ACZs-IIb and IVa (Table 1). Associated tree species of this system in ACZ-IIb were *P. cineraria, V. nilotica, Z. mauritiana, A. indica* and *S. oleoides* and the companion agricultural crop were pearl millet, moong bean, cluster bean, moth bean and sesame in 'Kharif', and wheat, barley, gram and mustard in 'Rabi' season. In ACZ-VIa, tree associates were *V. nilotica*, *Z.*

mauritiana and *A. indica* with intercrops maize, jowar (*Sorghum bicolor*), cotton, pearl millet, moong bean, and cluster bean during 'Kharif', and wheat, barley, gram and mustard in 'Rabi' season.

Vachellia nilotica based system: *Vachellia nilotica*-based agroforestry system was found distributed in Ib, IIa, IIIa, IIIb, IVa, IVb and V agroclimatic zones (Table 1). However, it was also observed in Gudamalani area of Barmer in ACZ-Ia and Khadin-system area of Jaisalmer in ACZ-Ic. It is most prevalent in certain pockets like Ghatol area of Banswara in ACZ-IVb. Other tree species found associated with *V. nilotica* were *P. cineraria, Dalbergia sissoo, A. indica, Z. mauritiana, A. excelsa* and *V. leucophloea*. Different intercrops associated with this system were bajra/pearl millet, cluster bean, moong bean, black bean, soybean, maize, paddy, cotton and groundnut during '*Kharif*' season, and wheat, barley, mustard, gram and lentil during 'Rabi' season under irrigation. There were slight variations in associates tree species and agricultural crops between different agroclimatic zones.

Vachellia nilotica subsp. cupressiformis based system: *Vachellia nilotica* subsp. *cupressiformis* (Kabuli Kikar Khajuria babul or Ramkanti) based system was found distributed in ACZ-IIb and ACZ-IIIa covering Pali and Dausa districts respectively (Table 1). This subspecies is characterized by (i) narrow and cypress-shaped crown, which allow understory crops to utilize sunlight effectively, (ii) branches makes a narrow angle with main trunk, and (iii) Straight trunk and cylindrical stem (Keerthika *et al*., 2021). Other tree species found associated with this agroforestry system were *V. nilotica, A. indica, A. excelsa, V. luecophloea* and *S. oleoides*. Different intercrops cultivated in this system were pearl millet, moong bean, cluster bean and groundnut during 'Kharif' season, and barley and gram during 'Rabi' season in respective district. The latter crops were cultivated mostly under irrigation.

Vachellia tortilis based system: *Vachellia tortilis*-based system was relatively less common and found distributed in ACZs- Ia and Ib (Table 1). However, it was also observed in Ic, IIa and IIb ACZs. Associated tree species other than *V. tortilis* in this system were *P. cineraria, T. undulata, Z. mauritiana, S. oleoides* and *C. decidua*, though there was slight variation in associated tree species and agricultural crops between different agroclimatic zones. The intercrops were pearl millet, moong bean, sesame and cluster bean in 'Kharif' season (rainfed). Groundnut, cotton, wheat, mustard, and cumin were cultivated under irrigation in this agroforestry system.

Zizyphus mauritiana based system: The most predominant horticultural system is *Z. mauritiana* based, which is adopted by farmers in Ia, Ic, and IIb agroclimatic zones, particularly under irrigation (Table 1). It is a spiny and evergreen tropical and sub-tropical fruit trees belonging to family Rhamnaceae. This system is prevalent in Barmer, Jodhpur, Jaisalmer, Bikaner, Nagaur and Pali districts. Most common crops in this system were moong bean, cluster bean and pearl millet cultivated during 'Kharif' season.

Tree density and growth

Tree density on farmlands: Average population of all tree species was 10.6 trees ha^{-1} on farmlands of Rajasthan that ranged between 2.4 tree ha^{-1} in ACZ-Ib and 23.6 tree ha^{-1} in ACZ-IIa. However, the density of dominant trees among ACZs varied from 1.5 tree ha^{-1} in ACZ-IIIb to 11.9 tree ha^{-1} in ACZ-IVb. Population density showed a decreasing trend with decreasing rainfall from southeast to northwest region of the state (Table 2). Among tree-based systems, population density was highest for *T. grandis* (30.0 tree ha^{-1}) based system, and lowest (across ACZs) of 3.7 trees ha^{-1} in *D. sissoo* based system with population of respective tree species being 25.0 tree ha^{-1} and 2.9 tree ha^{-1} respectively. Below state average population of dominant trees (5.9 tree ha^{-1}) was for *A. excelsa*, *P. juliflora*, *V. tortilis*, *D. sissoo*, *Z. mauritiana, S. oleoides, A. indica*, and *V. nilotica*. Other dominant tree species were above state average and were prominent in most of the ACZs. Tree density was strongly correlated with rainfall (r^2) = 0.23; p<0.001). ACZ × dominant tree interaction showed decline in *V. nilotica* density from 5.8 trees ha^{-1} in ACZ-V to 0.9 trees ha^{-1} in ACZ-Ib, *A. indica* from 5.0 trees ha^{-1} in ACZ-IVb to 0.4 tree ha^{-1} in ACZ-IIIa (Table 2). Population density of *A. excelsa* was 1.8-6.9 trees ha^{-1}, *V. leucophloea* from 2.0-4.1 trees ha^{-1}, *S. oleoides* from 1.9-8 trees ha^{-1} in different ACZs. Density of *P. cineraria* showed

Table 2. Distribution and population density (trees ha⁻¹) of tree species in agroforestry systems in different agroclimatic zones of Rajasthan

Tree Species	Density	Agroclimatic zone*										Mean
		Ia	Ib	Ic	IIa	IIb	IIIa	IIIb	IVa	IVb	V	
A. excelsa	TTD	-	-	-	23.5	-	9.6	3.3	-	-	-	12.1
	DTD	-	-	-	6.9	-	5.6	1.8	-	-	-	4.8
A. indica	TTD	11.8	-	-	40.6	7.5	1.8	3.3		30.0	-	15.8
	DTD	1.8	-	-	4.3	2.3	0.4	1.0		5.0	-	2.5
D. sissoo	TTD	-	2.5	4.8	-	-	-	-	-	-	-	3.7
	DTD	-	1.8	4.0	-	-	-	-	-	-	-	2.9
P. cineraria	TTD	15.1	-	8.2	23.8	7.3		-	-	-	-	13.6
	DTD	3.5	-	7.6	10.2	3.7		-	-	-	-	6.3
P. juliflora	TTD	7.6	-	-	-	-	-	-	-	-	-	7.6
	DTD	0.8	-	-	-	-	-	-	-	-	-	0.8
S. oleoides	TTD	6.4	-	-	-	12.0	-	-	-	-	-	9.2
	DTD	1.9	-	-	-	8.0	-	-	-	-	-	5.0
S. senegal	TTD	27.6	-	-	-	-	-	-	-	-	-	27.6
	DTD	23.7	-	-	-	-	-	-	-	-	-	23.7
T. undulata	TTD	13.9	-	7.8	15.3	-	-	-	-	-	-	12.3
	DTD	2.6	-	3.9	7.0	-	-	-	-	-	-	4.5
T. grandis	TTD	-	-	-	-	-	-	-	-	30.00		30.00
	DTD	-	-	-	-	-	-	-	-	25.00		25.00
V. leucophloea	TTD	-	-	-	-	8.0	-	-	8.8	-	-	8.4
	DTD	-	-	-	-	2.0	-	-	4.1	-	-	3.1
V. nilotica	TTD	-	2.9	-	14.6	-	3.7	3.3	11.2	8.7	6.7	7.3
	DTD	-	0.9	-	4.1	-	3.0	1.8	2.3	5.7	5.8	3.4
V. nilotica var. *cupressiformis*	TTD	-	-	-	-	19.2	14.0	-	-	-	-	16.6
	DTD	-	-	-	-	19.2	4.0	-	-	-	-	11.6
V. tortilis	TTD	9.7	31.9	-	-	-	-	-	-	-	-	20.8
	DTD	1.3	31.0	-	-	-	-	-	-	-	-	16.2
Z. mauritiana	TTD	8.0	-	9.6	-	8.0	-	-	-	-	-	8.5
	DTD	4.0	-	1.2	-	5.0	-	-	-	-	-	3.4
Mean	TTD	12.5	2.4	7.6	23.6	10.3	7.3	3.3	10.0	22.9	6.7	10.6
	DTD	5.0	11.2	4.2	6.5	6.7	3.3	1.5	3.2	11.9	5.8	5.9

*Agroclimatic zones as in Table 1. TTD- Total trees density; DTD- dominant tree density.

a large variation ranging between 3.5 tree ha⁻¹ in ACZ-Ia and 10.2 tree ha⁻¹ in ACZ-IIa.

Effect of climatic zone on tree growth: Average height, dbh, canopy diameter, basal area and canopy cover of the trees varied significantly (p<0.05) between the agroclimatic zones (Table 3). Trees were taller, greater in canopy diameter and canopy cover in ACZ-IIIb, whereas dbh and basal area were highest in ACZ-IIa. However, Duncan Multiple Range Tests (DMRT) showed non-significant (p>0.05) difference in trees height between ACZ-IIIb and ACZ-Ib, canopy diameter between ACZ-Ib and IIIb, and basal area between ACZ-Ia and ACZ-IIa. Trees were smaller in height and canopy diameter in ACZ-IIb, low basal area and canopy cover in ACZ-Ib and smallest dbh in ACZ-IVb. Height and dbh were negatively correlated (r=0.257 and 0.399, p<0.001) with tree density.

Tree structure and growth with agroforestry systems: Tree growth variables (height and dbh), basal area and canopy cover varied significantly (p<0.05) among the tree species (Table 4). Average tree height was 8.46 m across the species in the farmlands of Rajasthan. Trees of *D. sissoo, T. grandis* and *A. indica* were taller than other species. The shorter trees were of *A. excelsa, P. cineraria, P. juliflora, T. undulata, V. tortilis, V. nilotica, V. nilotica* var. *cupressiformis*, *S. oleoides*, *V. leucophloea*, and *Z. mauritiana*. For diameter growth, *S. oleoides* showed highest dbh, whereas stem of *Z. mauritiana* was thinner as compared to the other species. Most of the species observed in the study showed similar

Table 3. Effects of agro-climatic zones on tree growth variables in different agroforestry systems in Rajasthan. Values are mean ± 1SD of multiple replications

ACZ*	Height (m)	Dbh (cm)	Canopy diameter (m)	BA (m^2 ha^{-1})	Canopy Cover (m^2 ha^{-1})
Ia	7.01±2.53^{ab}	26.76±20.05^{a}	6.39±2.62^{ab}	4.84±4.04^{c}	222±299^{ab}
Ib	11.23±6.05^{d}	42.51±17.23^{d}	10.32±3.47^{e}	0.38±0.20^{a}	41±17^{a}
Ic	8.09±2.99^{ab}	34.13±11.49^{bc}	6.77±1.72^{ab}	3.77±2.13^{bc}	177±148^{ab}
IIa	8.21±2.61^{b}	34.99±12.59^{bc}	7.24±1.59^{c}	4.88±2.92^{c}	243±192^{b}
IIb	6.53±1.97^{a}	27.92±17.45^{a}	5.02±2.06^{a}	2.42±1.97^{ab}	120±121^{ab}
IIIa	8.73±1.91^{bc}	34.75±9.92^{bc}	8.56±2.38^{d}	3.28±2.62^{bc}	260±185^{b}
IIIb	11.73±1.20^{d}	33.09±3.92^{ab}	10.35±1.24^{e}	2.44±0.77^{ab}	453±241^{c}
IVa	7.44±1.57^{ab}	33.46±9.39^{ab}	7.70±2.37^{b}	2.52±1.40^{b}	156±152^{ab}
IVb	9.97±1.45^{c}	23.59±7.81^{a}	5.67±3.29^{ab}	3.49±3.10^{bc}	107+79^{ab}
V	8.33±1.40^{b}	31.05±12.41^{ab}	8.59±2.12^{d}	2.86±2.09^{bc}	266±225^{b}
One-way ANOVA					
F value	15.79	4.37	13.83	7.68	12.96
P value	<0.001	<0.05	<0.001	<0.001	<0.001

*ACZ-Agroclimatic zones as in Table 1. Values with different letter as superscript in a column indicate significant (p<0.05) difference.

growth pattern in both dbh and height, except *T. grandis* which was third lowest in dbh (Table 4). Average dbh, canopy diameter, basal area and canopy area across the species were 30.53 cm, 6.91 m, 0.45 m^2 ha^{-1} and 207 m^2 ha^{-1}, respectively. Canopy diameter was highest in *V. tortilis* and lowest in *T. grandis*. Some tree species like *P. cineraria*, *T. undulata*, *P. juliflora*, *A. excelsa* and *A. indica* were medium in canopy diameter. Basal area varied between 1.47 m^2 ha^{-1} for *S. oleoides* based system and 0.09 m^2 ha^{-1} for *Z. mauritiana* based system, whereas canopy cover ranged between 608 m^2 ha^{-1} in *S. senegal* and 53 m^2 ha^{-1} in *Z. mauritiana* based system. Canopy cover showed positive correlations with tree density (r=0.895, p<0.001) and basal area (r=0.795, p<0.001) and negative correlations with rainfall (r=-0.260, p<0.001).

Agricultural crop production

Grain yield of agricultural crops showed wide variations (p<0.001) because of ACZs, tree species and crop species and distance from the tree species under tree-crop interactions. Though varied in extent and depending upon the compatibility between tree species and the associated agriculture crops, there was reduction in grain yield of the crops in all agroforestry systems (except *P. ovata* with *P. cineraria* in ACZ-IIb) ranging between 9.4% and 79.8% (Supplementary Table 1).

Crop yield under tree canopy zone: Average grain yields of agricultural crops varied significantly (p<0.05) between ACZs across agroforestry systems, crop types and distance from the tree trunk. Variability in the grain yields was less in the western arid region as compared to the state average yields of 1.08 Mg ha^{-1} (mega gram ha^{-1}). The highest grain yield was 1.85 Mg ha^{-1} in ACZ-IIIa. It was followed by ACZ-IVa, -V, -IIIb and IVb, which were also significantly (p<0.05) different in grain yields (Fig. 2a). Lowest grain yield was in ACZs-Ia. Yield did not differ (p>0.05, DMRT) between Ic and IIa as well as between Ib and IIb zones. Grain yield was positively correlated (r=0.403, p<0.001) with annual rainfall. Irrigated zones demonstrated increased yields as compared to the rainfed ones.

When tree-based systems were considered, grain yield varied significantly (p<0.01) and yield ranged between 0.53 Mg ha^{-1} in association of *T. undulata* and 1.60 Mg ha^{-1} in association of *A. excelsa* showing 3.02-fold variation. However, crop yield was almost similar (p>0.05) in *A. indica* and *T. grandis* based systems. Likewise, average grain yield did not differ (p<0.05) between *P. juliflora, V. tortilis* and *P.* cineraria, *Z. mauritiana* and *S. senegal*, and between *S. oleoides* and *Z. mauritiana* based systems (Fig. 2b). *T. undulata*-based system showed lowest grain yield. When compared with state average, crops associated with *Vachellia* species and *A. excelsa* based systems gave about 12.2-51.7% higher yield, whereas yield under *S. senegal, T. undulata, P. cineraria, Z. mauritiana, S. oleoides,*

Table 4. Growth, basal area, canopy diameter and canopy cover of tree species in different agroforestry systems in Rajasthan. Values are mean±1SD of multiple replications

Tree Species	Height (m)	Dbh (cm)	Canopy diameter (m)	Basal area (m^2 ha^{-1})	Canopy cover (m^2 ha^{-1})	CC (%)
V. nilotica var. *cupressiformis*	$7.6±1.17d^{bcde}$	$24.23±5.1^{de}$	$3.9±0.46^{de}$	$0.37±0.32^{b}$	$99±50^{cd}$	0.99
V. leucophloea	$6.8±0.93^{def}$	$26.14±6.13^{cde}$	$6.6±1.22^{cde}$	$0.18±0.08^{b}$	$117±39^{cd}$	1.17
V. nilotica	$8.7±2.11^{bcd}$	$33.18±9.99^{bcd}$	$8.7±3.06^{bc}$	$0.32±0.33^{b}$	$214±185^{bcd}$	2.14
V. tortilis	$9.3±2.40^{bc}$	$32.56±11.24^{bcd}$	$11.1±4.30^{a}$	$0.13±0.09^{b}$	$158±142^{bcd}$	1.58
A. excelsa	$9.1±2.76^{bc}$	$36.85±16.91^{b}$	$7.7±1.01^{cde}$	$1.32±1.59^{a}$	$347±172^{bc}$	3.47
Z. mauritiana	$5.0±0.88^{f}$	$16.73±6.75^{e}$	$5.0±1.90^{fgh}$	$0.09±0.11^{b}$	$53±47^{d}$	0.53
P. cineraria	$8.2±2.02^{bcde}$	$35.67±10.95^{bc}$	$7.0±1.58^{de}$	$0.54±0.50^{b}$	$198±173^{bcd}$	1.98
S. senegal	$6.7±2.26^{ef}$	$18.30±8.99^{e}$	$5.8±2.10^{efg}$	$0.59±0.38^{b}$	$608±440^{a}$	6.08
A. indica	$9.5±2.70^{b}$	$36.54±13.76^{b}$	$7.5±2.09^{cde}$	$0.41±0.22^{b}$	$179±151^{bcd}$	1.79
P. juliflora	$8.7±1.61^{bcd}$	$32.22±7.46^{bcd}$	$7.5±1.93^{cde}$	$0.15±0.01^{b}$	$83±28^{cd}$	0.83
T. undulata	$8.2±2.58^{bcde}$	$34.19±9.26b^{cd}$	$6.6±1.84^{def}$	$0.31±0.30^{b}$	$115±118^{cd}$	1.15
T. grandis	$11.3±0.36^{a}$	$19.09±4.29^{e}$	$3.1±0.10^{ij}$	$0.74±0.06^{b}$	$129±44^{cd}$	1.29
S. oleoides	$7.5±2.65^{cde}$	$89.81±34.26^{a}$	$7.8±2.69^{cd}$	$1.47±0.68^{a}$	$122±71^{cd}$	1.22
D. sissoo	$11.8±4.22^{a}$	$35.91±14.39^{bc}$	$8.8±2.40^{bc}$	$0.19±0.21^{b}$	$120±113^{cd}$	1.2
One-way ANOVA						
F value	17.12	49.93	18.71	28.68	48.16	3.31
P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01

CC: canopy cover. Values with different letters as superscript in a column indicate significant ($p < 0.05$) difference.

V. tortilis and *P. juliflora* system was 29.1-54.9% low (Fig. 2b).

While considering agricultural crops across ACZs, agroforestry systems and distance from tree, average grain yield varied ($p<0.05$) from 0.36 Mg ha^{-1} for Taramira to 2.64 Mg ha^{-1} for maize with 7.3-fold variation (Fig. 2c). The yield of *E. sativa*, *V. aconitifolia*, *C. cyminum*, *C. sativum* and *L. culinaris* was <0.5 Mg ha^{-1}, whereas the yield in *P. ovata*, *V. radiata*, *V. mungo*, *C. tetragonoloba*, *G. max* and *V. unguiculata* was 0.5-1.0 Mg ha^{-1}. The yields in other crops were >1.0 Mg ha^{-1}. Barley, gram, groundnut, jowar, maize, mustard, paddy, pearl millet and wheat showed above state average yield. For distance from tree trunk, there were significant ($p<0.001$) spatial variations in crop yields across ACZs, agroforestry systems and crop types in Rajasthan. Lowest crop yield (0.72 Mg ha^{-1}) was at 1 m distance improved with increase in distance from tree trunk i.e., 1.44 Mg ha^{-1} at canopy edge and 1.77 Mg ha^{-1} in control. However, Isabgol, moth bean, cluster bean and moong bean showed 0.8-32.6% higher yield at the canopy edge of *P. cineraria* than in the control plot.

All interaction terms of four-way ANOVA were significant ($p<0.05$) indicating interdependency of ACZs, tree-based systems, crop types and distance from trees factors (Supplementary Table 2). Yield of barley, gram, jowar, maize, paddy, pearl millet, and wheat were >2.0 Mg ha^{-1} in *A. excelsa*, *A. indica*, *V. leucophloea*, *V. nilotica* and *V. nilotica* var. *cupressiformis* based systems in irrigated areas of IIb-V agroclimatic zones (Supplementary Table 1). Yield of *A. hypogaea* was highest with *V. nilotica* and *V. nilotica* var. *cupressiformis* in ACZ-IIIa, and that of *C. tetragonoloba* with *D. sissoo* in ACZ-Ic. Yield of pearl millet in *P. cineraria*-based system was almost same in ACZ-Ic and IIa. Moong bean exhibited highest yield in ACZ-IIa with *A. excelsa* and in IIb with *P. cineraria*. Cotton exhibited high yield with *V. nilotica* in ACZ-IVa. Combination of Isabgol and *P. cineraria* system showed positive interaction where crop yield was 43.6% higher in ACZ-IIb (Supplementary Table 1).

Crop yield reduction: Crop yields were greater in the control plots as compared to the canopy zone plots (near tree trunk and canopy edge). Average reduction in grain yield under tree canopy as compared to the control plot was 37.0% (Table 5). Among ACZs (across all other factors), the reduction in crops yields was 41.7-47.3% in ACZs- V, Ia, and Ib, whereas other ACZs showed 23.0% to 34.8% reduction. While considering agroforestry systems (across ACZs, crop types and distance from tree), crop yield reduction ranged between 20.4% under *P. cineraria* and 56.5% under *S. oleoides* based system. Less than 30% yield reduction was under *P. cineraria* and *A. excelsa*, whereas >50% reduction was in *P. juliflora* and *S. oleoides* based systems. Among agricultural crops across all other factors, reduction in crop yield ranged between 15.9% for *V. unguiculata* and 79.8% for *Eruca sativa.* Average yield reduction by <35% was recorded in *H. vulgare*, *C. tetragonoloba*, *P.*

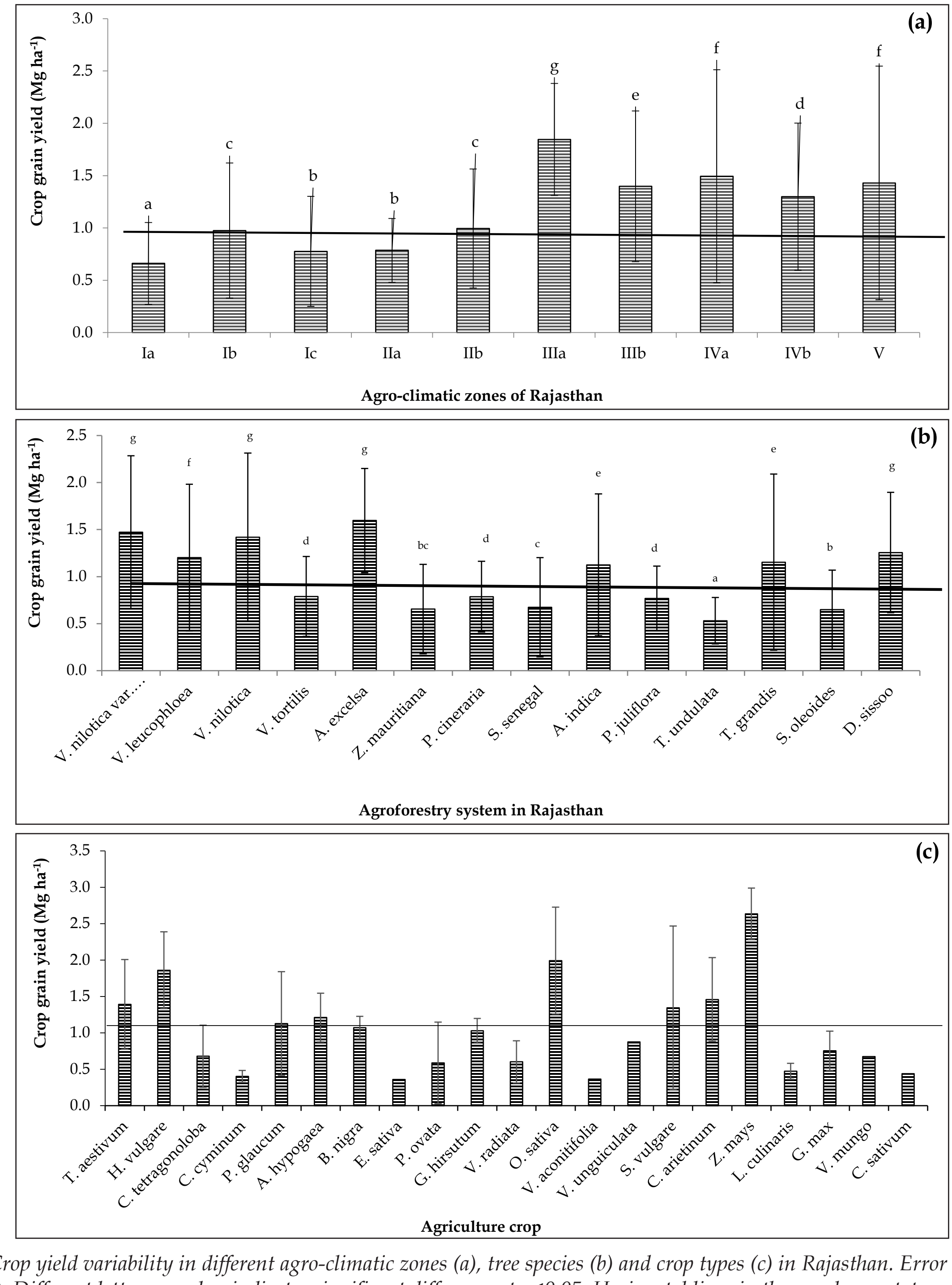

Fig. 2. Crop yield variability in different agro-climatic zones (a), tree species (b) and crop types (c) in Rajasthan. Error bars are ± 1SD. Different letters on a bar indicates significant difference at p<0.05. Horizontal lines in the panels are state average.

Table 5. Crop yield reduction under interactive effects of ACZs, agroforestry systems, crop types and distance from tree trunk as compared to control in Rajasthan. Values are mean±1SD of multiple replications

ACZs/Tree system/Crops	Yield in control (Mg ha^{-1})	Crop yield reduction (%)		
		Near tree trunk	Canopy edge	Mean
		Agroclimatic zone		
Ia	1.28±0.69	63.13±15.81	30.15±16.91	46.64±14.40
Ib	2.05±1.46	67.37±20.60	27.28±14.03	47.33±14.94
Ic	1.03±0.63	46.74±24.59	8.11±7.16	27.42±10.05
IIa	1.06±0.47	38.88±21.09	6.99±14.91	22.94±16.99
IIb	1.61±0.90	51.27±34.36	16.88±22.28	34.08±26.43
IIIa	2.80±0.77	54.55±11.67	11.98±9.80	33.26±7.82
IIIb	2.04±0.98	36.71±6.88	25.47±13.12	31.09±6.96
IVa	2.17±1.24	58.61±15.15	10.90±14.56	34.76±11.65
IVb	2.06±1.04	56.17±18.83	13.49±8.36	34.83±8.73
V	2.76±2.66	66.82±14.43	16.72±11.90	41.74±12.50
		Tree based agroforestry		
Senegalia senegal	1.15±0.91	59.46±18.33	24.44±12.34	41.96±13.13
Vachellia tortilis	1.53±0.73	71.01±7.11	25.07±14.23	48.03±8.67
Prosopis cineraria	1.01±0.47	38.10±34.41	2.54±13.57	20.33±21.83
Prosopis juliflora	1.64±0.63	75.75±3.75	31.60±10.04	53.65±3.18
Salvadora oleoides	1.50±0.60	66.92±15.88	46.10±22.51	56.52±17.88
Tecomella undulata	0.85±0.51	45.81±19.66	19.94±16.53	32.89±17.32
Zizyphus mauritiana	1.03±0.70	52.32±22.48	19.10±17.75	35.70±14.71
Vachellia nilotica	2.32±1.56	57.47±16.74	15.53±15.04	36.49±13.41
Dalbergia sissoo	2.33±1.23	60.03±30.01	21.46±14.93	40.73±20.16
Ailanthus excelsa	2.27±0.78	42.76±15.11	12.93±11.67	27.86±11.80
Azadirachta indica	1.93±1.06	61.52±18.72	25.58±13.22	43.54±9.65
Vachellia luecophloea	2.05±1.09	58.60±16.03	22.05±19.67	40.33±16.47
V. nilotica var. *cupressiformis*	2.13±1.10	53.13±11.47	12.93±12.13	33.05±10.63
T. grandis	1.84±1.69	55.55±27.79	7.95±4.17	31.75±11.81
		Crop type		
Ttriticum aestivum	2.28±0.91	58.36±18.38	19.42±15.69	38.89±11.75
Hordeum vulgare	2.89±0.94	57.88±13.52	10.63±1.71	34.25±6.48
Cyamopsis tetragonoloba	0.98±0.51	51.47±20.18	15.78±12.97	33.62±15.82
Cuminum cyminum	0.70±0.14	59.00±9.87	25.23±9.90	42.13±6.73
Pennisetum glaucum	1.68±1.04	46.29±16.08	17.09±13.71	31.69±12.24
Arachis hypogaea	2.00±0.41	50.94±18.82	26.10±17.71	38.51±17.62
Brassica nigra	1.98±0.28	70.92±13.60	19.15±15.87	45.03±9.81
Eruca sativa	1.78±0.15	86.00±0.00	73.60±0.00	79.80±0.00
Plantago ovata	0.70±0.00	29.17±72.80	17.17±43.19	23.17±57.95
Gossypium hirsutum	1.84±0.43	64.60±22.14	19.00±19.19	41.80±16.19
Vigna radiata	0.91±0.38	49.85±18.84	17.15±21.08	33.50±18.12
Oryza sativa	5.49±1.48	89.93±9.25	38.30±5.30	64.10±4.97
Vigna aconitifolia	0.64±0.00	93.80±0.00	-7.80±0.00	43.00±0.00
Vigna unguiculata	1.04±0.00	17.30±0.00	14.40±0.00	15.90±0.00
Sorghum bicolor	1.98±1.16	62.07±12.91	14.00±21.33	38.03±15.78
Cicer arietinum	2.58±0.50	58.83±19.61	26.17±22.85	42.53±21.20
Zea mays	3.62±0.50	52.80±6.09	1.40±0.00	27.13±0.00
Lens culinaris	0.85±0.07	67.20±16.40	22.35±0.21	44.75±8.27
Glycine max	1.15±0.52	44.83±12.60	19.45±6.74	32.13±7.37
Vigna mungo	0.97±0.00	53.60±0.00	7.20±0.00	30.40±0.00
Coriandrum sativum	0.86±0.00	74.40±0.00	23.30±0.00	48.80±0.00
Mean	1.77±1.16	55.23±21.61	18.68±16.83	36.95±16.58

glaucum, *P. ovata*, *V. radiata, V. unguiculata*, *Z. mays*, *G. max* and *V. mungo*. As compared to control, average decline in crops yield was by 55.2% at 1 m and 18.7% at canopy edge of the trees. At near tree, yield reduction ranged from 38.9-67.4% between ACZs, from 38.1-75.8% between agroforestry systems, and from 17.3-93.8% between crop types. Variations due to respective factors at canopy edge were from 7.0-30.2%, 2.5-46.1% and from -7.8-73.6% (Table 5). *V. aconitifolia* showed an increase in yield at canopy edge. Crop yield reduction was least at the canopy edge of *P. cineraria*, whereas it was about 8.0-15.3% at canopy edge of *T. grandis*, *V. nilotica* var. *cupressiformis* and *A. excelsa* (Table 5). More than 50% observations showed higher yield at the canopy edge of *P. cineraria* tree than that in the control plot. The reduction in crop yield was 25.2-46.1% at the canopy edge of *V. tortilis, S. senegal*, *P. juliflora* and *S. oleoides*. Least reduction in yield of pearl millet was with *Z. mauritiana* in ACZ-IIb, and with *T. undulata* and *P. cineraria* in ACZ-Ia (Supplementary Table 1).

Discussion

Agroforestry systems

A wide variation in climatic, edaphic, socioeconomic, and cultural conditions in Rajasthan resulted in 14 numbers of dominant tree-based traditional agroforestry systems with varying density and growth. This was also shown by involvement of 21 dominant agriculture crops that gave 111 tree-crop combinations. Cultivation of 15 crop species in association of *V. nilotica* and 8 crops with *P. cineraria* indicated their social acceptance and better suitability under agroforestry systems as compared to other tree species. Less number of crop species cultivation in association of *P. julflora* and *Tectona grandis* indicated their least preference because of competitiveness by surface spreading roots and shading (Yoda *et al*., 2012; Shackleton *et al*., 2015; Shiferaw *et al*., 2021; Mankur *et al*., 2022). However, availability of a particular tree-based agroforestry system in an agroclimatic zone was because of adaptability of the species to the climatic and edaphic conditions and soil water availability through rainfall as indicated by wide variability in density of *Z. mauritiana, A. excelsa*, *D. sissoo, P. cineraria* and *S. oleoides* in different ACZs (Endale *et al*., 2017). It was also supported by positive correlation (r=0.38, p<0.01) between tree density and rainfall. However, it also depends on the tree characteristics and its social acceptability as indicated by highest density *T. grandis* (25 tree ha^{-1}) and low density (<5.9 tree ha^{-1}) for *A. excelsa*, *P. juliflora*, *V. tortilis*, *D. sissoo*, *Z. mauritiana, S. oleoides, A. indica*, and *V. nilotica*. Density ranging from 6.3 to 23.7 tree ha^{-1} for *P. cineraria,* and *V. nilotica* var. *cupressiformis* and *S. senegal* was very much like the observation of Tewari *et al.* (2014) for *P. cineraria* with 8.2 -14.2 trees ha^{-1} in traditional farming system. Decreasing tree density from east to west was very much correlated to decreasing rainfall (r^2 = 0.23, p<0.001). For example, *P. cineraria* is available in all rainfall zones of Rajasthan, but its density decreases with decreasing rainfall. Likewise, *V. nilotica* tree was observed in all rainfall zones, but its density was higher in relatively high rainfall zone ACZ-IVb, where soils are deep and medium in texture (Hussain, 2015). Thus, poor soil status and low water availability affected tree density negatively ACZ IIIb (3.3 trees ha^{-1}). Ajit *et al.* (2016) also recorded average tree density of 6.95 to 12.42 tree ha^{-1} in the arid zone of Rajasthan. However, Density of *Salvadora* and *Prosopis cineraria* used to be high in the cultivated fields earlier, but with the introduction of tractor and intensive cultivation, the farmers are now removing *Salvadora* trees from their field, whereas least preferred species *V. tortilis* and *P. juliflora* exhibited their population around 0.5-1.2 tree ha^{-1} (Bhati *et al*., 2017).

Tree growth

Significant variations (p<0.01) in most of the growth variables between ACZs were because of variation in climatic conditions like relatively high rainfall, soil fertility and soil water availability (Brandt *et al*., 2019). Żywiec *et al*. (2017) also observed a clear, strong relationship between tree growth and climate, with annual precipitation being the most important climate factor enhancing radial growth. Greater tree height and canopy diameter in ACZ-Ib, which is under canal water irrigation (Ganganagar and Hanumangarh districts) might be because of availability of conducive soil moisture. Shortest tree size in ACZ-IIb was due to edaphic conditions and species growth characteristics (Nath *et al*., 2006; Pappas *et al*., 2020). Negative effects of relatively greater saline soils in this

ACZ might have also affected the tree size. However, taller trees in ACZ-IIIb and dbh in ACZ-Ib was a resultant of soil resources availability and competitive effects under increased tree density. It was also supported by negative correlation (r=0.257 and 0.399, p<0.001) between height/dbh and tree density. Highest basal area and canopy cover in ACZ-IIa and IIIb, respectively was due to species growth characteristics and higher density plantations (Tewari *et al*., 2014). Most influencing factors of basal area and canopy cover was tree density that was evidenced by significant positive correlations of canopy cover with tree density (r=0.895, p<0.001) and the basal area (r=0.795, p<0.001). However, effect of species traits was supported by lowest basal area and canopy cover for *Z. mauritiana* and their highest values for *S. oleoides* and *S. senegal* respectively (Rollinson *et al*., 2015). Lowest basal area (0.38 m^2 ha^{-1}) and canopy cover (41 m^2 ha^{-1}) in ACZ-Ib was due to low density of trees (Bhati *et al*., 2004). Canopy management (pruning and lopping) in traditional agroforestry is a general practice in the region to reduce resource competition between tree and the associated agricultural crops favouring increased crop yield in Rajasthan (Mann and Saxena, 1980).

Productivity of companion crops

Crop yield ranging from 0.66 Mg ha^{-1} in ACZ-Ia to 1.85 Mg ha^{-1} in ACZ- IIIa was because of complex interaction among tree-crop species, soil, and climate (precipitation) in different agroclimatic zones (Hussain, 2015; Meena *et al*., 2016). It was also shown by positive correlation (r=0.403, p<0.001) between crop yield and annual rainfall and variability in extent of crop yield reduction due to ACZs, tree and crop species and distance from tree trunk. Highest crop yield in ACZ-IIIa as compared to the other ACZs was due to relatively higher rainfall (838 mm in year 2016-17), dominance of alluvium soil as well as use of supplemental irrigation in both 'Kharif' and 'Rabi' seasons (Singh and Kumar, 2016). It suggests that irrigation is an effective strategy to increase crop yields and food security. However, variability in crop yield was also influenced by type of agroforestry systems, tree and crop species and extent of tree-crop interactions (distance from tree trunk). While crop yield range of 0.53 Mg ha^{-1} under *T. undulata* to 1.60 Mg ha^{-1} under *A. excelsa* highlight the importance of tree species, reduced crop yield in all agroforestry systems demonstrated the competitive interactions of tree species on the companion crops (Singh and Rathod, 2007a & b; Singh, 2009; Singh *et al*., 2014). About 4.5-51.7% higher crop yield in *A. excelsa, A. indica, D. sissoo, T. grandis V. nilotica, V. nilotica* var. *cupressiformis* and *V. leucophloea* based system and 29.1-54.9% low yield in *S. senegal, T. undulata, P. cineraria, Z. mauritiana, S. oleoides, A. tortilis* and *P. juliflora* based system as compared to state average (across crop species) was because of variations in rainfall, soil water and nutrients availability and crop species cultivated (Bhati *et al*., 2017). Competitive use of available resources between tree and crop species affected yield of companion crops negatively (Puri *et al*., 1994; Yadav *et al*., 2005).

Decrease in crop yield by 55.2% near the tree trunk (across tree species) and 18.7% at the canopy edge as compared to the control plot exhibited a decrease in competitive tree-crop interactions for soil water, nutrients, and light with distance from tree under reduced effects of root access and shading by tree canopy (Gao *et al*., 2013; Swieter *et al*., 2021). Similar observation was also reported in experimental plantation, where yield in agricultural crops increased with increase in soil water and nutrient availability with distance from tree trunk/alley (Singh *et al*., 2007; Singh, 2009; Swieter *et al*., 2021). Lowest crops yield reduction at the canopy edge of *P. cineraria* was because of relatively more favourable conditions on companion crops as compared to the other tree species (8.0-15.3% reduction under *T. grandis, V. nilotica* var. *cuppresiformis* and *A. excelsa*). It was also supported by 50% observations showing higher yield at the canopy edge of *P. cineraria* because of synergistic effect of *P. cineraria* on crops as observed in other studies (Singh *et al*., 2007; Singh *et al*., 2014). Relatively greater reduction in crop yield in association of *S. oleoides, P. juliflora, S. senegal*, and *V. tortilis* was because of surface spreading lateral roots and canopy cover affecting availability of soil resource and solar radiation reaching to the ground (Kahi *et al*., 2009; Coulibaly *et al*., 2014). The effect of *A. indica, D. sissoo* and *V. nilotica* tree species was even beyond the spread of the canopy (personal observations). The highest reduction in crop yield under *S. oleoides* was due to its evergreen nature, dense canopy, and utilization of greater amount of soil resources by its surface spreading roots suppressing crop yield as compared to those of deciduous and semi deciduous tree species (Muthuri *et al.*, 2005). This was the effect of tree species on crop yield, but reduction in crop yield from 9.4% for *V. radiata* to 79.8% for *Eruca sativa* highlighted the effects of crop species and their cultivars. Increased yield of Isabgol, moth bean, cluster bean and moong bean by 1.8- 32.6% (canopy edge) with *P. cineraria* exhibited the impact of crop species adaptability and compatibility to climate and tree components of the agroforestry systems. This suggests proper selection of suitable tree-crop combinations for different climatic conditions and adoption of appropriate management strategies for maximizing yield of the system.

Conclusion

Results of this study show a complexity of site- and species-specific responses of agroforestry systems to varying climatic, edaphic, and socioeconomic conditions in Rajasthan. This led to 111 tree-crop combinations derived by interactions of 21 crops and 14 tree species on farmlands. Rainfall, soil conditions and species adaptability appeared important factors influencing distribution of different tree-based agroforestry systems, density and growth of the tree species and crop yields as well. Tree density and growth decreased with decrease in rainfall from east to west in the state. *Prosopis cineraria* was prominent agroforestry system in western arid region, whereas *V. nilotica* was dominated in south-eastern semi-arid region of Rajasthan. About 2.8-fold variations in crop yield between ACZ-Ia and ACZ-IIIa highlights the suitability of tree and crop combinations and their interactions with climate and soils. Tree-crops competition decreased with increase in distance from tree, but extent of reduction in grain yield was 22.9-47.3% in different ACZs. *S. senegal, T. undulata, P. cineraria, Z. mauritiana, S. oleoides, V. tortilis* and *P. juliflora* based system in arid region exhibited 29.3-54.9% lower, whereas *V. nilotica*, *D. sissoo*, *A. indica, T. grandis* and *V. leucophloea* based system showed 4.5-51.7% higher grain yield over state average. Thus, crop yield depended on interactive outcome of climate, tree species and intercrops as some species like *P. cineraria* indicated better compatibility with agricultural crops. This highlights the importance of climate, tree size and compatibility between tree and intercrop in enhancing land productivity. Hence these agroforestry systems can suitably be adopted following applicable management of tree roots and canopy along with increasing tree cover by planting and managing natural regeneration for improved food security and farming system resilience towards climate change.

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