

Quantifying the yield loss pattern in paddy crop within a native tree-based riverine agroforestry system in Chhattisgarh, Central India: Implications to food sustainability and climate smart farming

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Abstract

Riverine agroforestry is a most diverse, dynamic and widely adopted in tropical agroecosystem along river catchments contributes to climate resilient farming and restoring rivers flow. We estimated the yield loss in paddy cultivar MTU7029 grown with *Acacia nilotica*, *Butea monosperma*, *Mangifera indica*, *Terminalia arjuna*, and *Terminalia tomentosa*. Tree crop interaction study was performed for two crop cycle (year 2021 and 2022) covering entire grid points of 100km river stretches, utilizing the same farmer fields, crop variety, and tree species. Additionally, two other factors, namely stem diameter (10–40, 41–80, 81–120, and > 120 cm DBH) and tree density (10, 20, 40, 60 trees ha⁻¹) were taken into account for the most abundant tree species *T. arjuna* at grids 5, 8 and 10 of riverine ecosystem. For species specific interaction, 36 trees and diameter and density class assessment, 30 trees were employed from the farmer's fields. Sample plots of 1m² size were established in standing crops at 2m, 8m, 15m, and 25m distances along a transect line from both sides of the tree, oriented in an east-west direction. Results showed a negative impact of trees on crop as Paddy yield reported 3.64 t ha⁻¹ at 2m and 5.52 t ha⁻¹ at 25m distance from the tree in crop field. Adverse effect of trees continued to decline paddy tiller and hills by 51% and 10.93% respectively in tree proximity. A large trees with big canopy *M. indica* and *T. tomentosa* were found most negative for crop yield than moderate to small canopy species *A. nilotica*, *B. monosperma* and *T. arjuna*. The large diameter trees led to the greater yield loss of 42.53% than the lower diameter trees. Farmland trees between 40–60 ha⁻¹ found to limit the yield by 66.45% when close to trees, however the yield loss was less with decreasing tree densities in the crop fields. The tree shade was observed to be the most influencing factor on yield loss of paddy than the other factors. Therefore, site specific tree selection based on morphological parameters such as height, canopy structure, and tree density up to 10–20 ha⁻¹ can promoted for the riverine agroecosystem. Regular canopy management and removal of exploitable diameter tree may also compensate the yield loss through intermediate income and yield loss reduction of paddy yield. Adoption of such practices may contribute towards climate resilient smart agroforestry practice expansion in riverine agroecosystem.

Introduction

Riverine agroforestry stands apart from conventional agroforestry systems because of its diverse biodiversity and greater number of trees, which help tackle global issues related to both productive and protective services. (Chandra and Singh, 2018; Rodenburg et al., 2022; Shukla et al., 2025a). This ecosystem favours paddy production in South East Asia enabling high moisture regime and water stagnation adopted for high yielding paddy cultivars (Kumar et al., 2010; Bouman et al., 2007; Kumar et al., 2013; Thevs et al., 2019). However, paddy productivity in such areas has become challenging due to destruction in riverine habitat, mining activities, and unpredicted monsoon resulting to a drying rivers. Evolving a climate resilient self-sustaining farming systems need urgently to adopt smart agriculture to cope up the negative environmental externalities and food security (Wezel et al., 2020). Undoubtedly, tree integration at farmlands adjacent to rivers form a green belt, and boost ecosystem services (Sinclair and Hitinayake 2000), protect soil erosion through root binding and reducing the rain drop velocity through tree canopy (Zuazo and Pleguezuelo, 2008). Moreover, tree contributes to the efficient recycling of nutrients by adding mulches, leaf and root turnover (Maclean et al., 2003; Barrios et al., 2012; Karki et al., 2018). Thus tree based farming system approaches are often more effective in regulating, supporting and cultural ecosystem services (Pagella and Sinclair, 2014) such as microclimate buffering, amelioration of soil properties and water infiltration and water table maintenance (Bayala et al., 2014; Fletcher et al., 2019; Sunderland et al., 2018; Ong and Kho 2015; Luedeling et al., 2016; Dawson et al., 2018; Chandra and Singh, 2018; Chandra et al., 2022; Shukla et al., 2025a). The potential of agroforestry practices to mitigate climate change and increase carbon sequestration has also been widely studied (Kuyah et al., 2013, Chandra et al., 2018; Rosenstock et al., 2014 Jose, 2009; Kumar et al., 2020; Rodenburg et al. 2022). However, the

expansion of the agroforestry system in paddy dominated areas are limited and confined to some African and south eastern countries (Miyagawa et al., 2017; Rodenburg et al., 2022; Koch et al., 2025). The non-expansion of agroforestry believes to the yield loss of crop and income of farmers (Chandra, 2018; Chandra and Singh, 2018, Pardon et al., 2025).

In actuality, though, its reach is restricted to a few innovative, sizable farmers in the tropical region. This approach needs to spread as quickly as possible to all agricultural communities, regardless of land size and agroclimatic conditions, in the context of climate change and food security (FAO, 2020). The negative and direct effects of trees on crop output are proven to be a significant barrier to the growth of agroforestry (Rao et al., 1998). Allopathic effects (Xuan et al., 2004; Khaliq et al., 2012; Kumari et al., 2016), tree shadow (Roder and Maniphone, 1998), and crop-tree competition for resources were the main causes of this negativity in the past. Depending on the degree of competition for growth resources between the woody component and the related crops which may also be impacted by site conditions, trees can have a complimentary or competitive effect on crops. There are instances where agricultural crop production is said to be decreased with tree integration (Chemura et al., 2021, Reuse et al., 2025). Large canopy shade on crops can place significant production restrictions on them, particularly in agroforestry systems based on Paddy. Because the benefits of agroforestry rely on site-specific responses of trees-crop systems and farming techniques, not all agroforestry treatments can be replicated elsewhere (Coe et al., 2014). These factors, along with unfavourable opinions held by peasant farmers, are impeding the advancement of agroforestry. As a result, scientific research is required to address the primary issues with Paddy agroforestry, such as the interactions between different system components and the vast geographical domains and timescales over which trees and crops interact at farmland (Smith et al., 2015; Rodenburg et al., 2022). Since the yield seems to be as the main indicator of quantitative performance of farmlands crops, its quantification to agroforestry models become a key to evaluate systems sustainability and food security. Efforts are being done to improve the self-sustenance in agriculture by equipping fields with the concept of neutral farming, organic farming and natural farming where the integration of perennial vegetation is increasingly advocating climate smart agriculture and sustainable farming (Garrity et al., 2010; Glover et al. 2012; Chandra, 2014; Rajesh Kumar et al., 2022; Muhie 2022). Such approaches needs to be propagated to save the soil health from the increasing effect of chemical fertilizers and pesticides in the cropping system (Angon et al., 2023; Terrer et al., 2021; Shinde et al., 2019).

The high sensitivity of global warming and climate change results in drying out riverine habitat, unpredictable monsoons, and high input costs, making such Paddy-growing practices difficult (Rodenburg et al., 2022). Thus, in order to practise smart agriculture and prevent detrimental environmental externalities, a self-sustaining farming system must be developed quickly (Wezel et al., 2020). Although agroforestry is a tried-and-true method of agro-ecological intensification, Paddy is not as often planted with trees as other crops because it needs more direct sunshine and conditions of water stagnation (Garrity et al., 2010; Glover et al., 2012). Paddy reported less suitable to be intercropped with taller and more competitive species (Akanvou et al. 2001) and because paddy crop requires anaerobic soil condition, which are less favourable for many tree species (Kramer and Kozlowski, 1979). The regional differences that how and how many trees are integrated with paddy may be the other reason of a less obvious paddy in agroforestry. Worldwide, paddy stands out as a staple food for over half of the world's population (Khush, 2005). However, paddy faces numerous challenges, including the need for increased productivity (Peng et al., 2006) and the necessity of adopting sustainable agricultural practices to mitigate environmental degradation (Vermeulen et al., 2012). Farmers simply need to maintain the trees and take care of tending operations to lessen the tree canopy and ease of farm equipment movements during farming activities (Kosaka et al, 2006; Pham et al., 2015; Miyagawa et al., 2017; Chandra, 2018; Dumrongrojwatthana et al., 2020; Daum, 2023).

The riverine Paddy agroforestry system, which stops soil degradation (Shinde et al., 2019) and protects Paddy crops from unfavourable local environments, is specifically used in the state of Chhattisgarh for agricultural intensification and multiple output (Bargali et al., 2009; Miyagawa et al., 2017; Watanabe et al., 2017). The farm produces more when the riverine trees are purposefully allowed to grow to the levees and floor (Chandra and Singh, 2018; Barrios et al., 2018; Nair, 2012, Shukla et al., 2025a). There are reports which alarm the negative impacts of trees on crops due to various reasons such as shadow of the tree, allelopathic effect, nutrient competitions, etc. (Kumari et al., 2016; Pardon et al., 2025), and more directly the shade of trees (Roder and Maniphone, 1998). Negative tree-crop interaction become more prominent especially when trees grows naturally than the well managed tree plantations. Therefore, all the interventions of agroforestry cannot be replicated everywhere as the agroforestry benefits varies on site specific responses of trees-crop system and farming contexts (Coe et al., 2014). Due to these reasons, the progress in agroforestry is held back concerning risk factors and negative perceptions of farmers towards agroforestry. To appraise the paddy based riverine agroforestry as adaptation measure to climate change, we shall take into account region-specific environmental conditions and the potential risks and benefits of trees in future farming (Rodenburg et al., 2022). The current study evaluated the effects of riverine agroforestry species on Paddy crop yield dynamics under farmer-field conditions. In riverine agroforestry practices along the Lilagar river in Chhattisgarh, tree species, diameter classes, and tree density (populations) were taken into consideration while quantifying the loss of Paddy yield due to tree cop interaction.

Materials and methods

Study site:

The study area lies in the riverine area of the river Lilagar which is a tributary of the Sheonath and Mahanadi rivers of Chhattisgarh, India. It is located between latitudes 21°44' N to 22°01' N and longitudes 81°20' E to 81°40' E (Fig. 1). This river originates from the Uda dam in Korba district and ends at the Sheonath river at Deverghatta in Jangir Champa district. The total length of the river is 135 km, while its catchment area covers approximately 1538 km². The second-third length of the river at higher elevations is occupied with natural forests, while its lower basin supports tree-based agroforestry systems and crop cultivation practices. The region has a tropical monsoon climate with an average annual rainfall of around 1200–1400 mm. The average temperature ranges from 22°C to 34°C. The communities that adjoin the river Lilagar rely on the river for their livelihoods and irrigation of crop fields.

Sampling methods:

The present study was carried out during April 2020 to December 2022 for 03 consecutive years and two crop cycles to consider multi season effects, comprising an extensive field survey along the entire river length in order to identify prevailing agroforestry practises. A total of 10 grid points were selected along the river at a 10 km interval, covering 100 km of river length and consisting of agroforestry and agriculture practises. Four sample plots were established randomly at each grid point of 1 ha each. Thus, a total of 4 ha is covered at each grid, and total 40 plots (40 ha) across river lengths. All the grids/ plot were laid out within 500m from the centre of the river in both the side.

Five tree species *A. nilotica* (L.) Delile (S1), *B. monosperma* (Lam.) Taub. (S2), *M. indica* L. (S3), *T. arjuna* (Roxb.) Wight & Arn (S4), *T. tomentosa* Willd (S5) were selected randomly considering 3 grids for one species covering entire stretches of riverine ecosystem adjacent to the Lilagar river. Species selection was done based on their occurrence to different grids such as S1 – from grids 5, 6, 9; S2–2, 3, 7; S3–4, 9, 10; S4–5, 8, 10 and S5 – grids 1, 8, 9. Tree species were available to farmer's field and well maintained on levees in North South orientation at a distance

between 5-6m apart. Each species experiment covers 3 grids, 12 sample plots (4 plots/grid), and 3 individual tree stems/plots (total 36 stem/species) were chosen. Tree- crop interaction effect was studied by laying out sample plots of 1m x 1m size in standing crop field cultivar MTU 7029 (Swarna) initiating from the stem at varying distances 2m, 8m, 15m, and 25m aliened in East-West direction of transect line (Fig. 2). Measurements of crop height, the number of tillers, and the number of paddy hills (m^2) were recorded individually from each plot in species-specific grids. We adhered to the methodologies proposed by Khan and Ehrenreich (1994); Karki et al. (2018); and Asmamaw (2017) in their studies on tree-crop interactions. The paddy yield was determined by manually harvesting from the designated sample plots assigned for species specificity at various grid locations prior to the field harvest at maturity, which occurred between November 15th and 25th in 2021 and 2022. Following the analysis of data from the sample plots, the parameters of paddy crop growth and yield were converted to a per-hectare basis. Crop yield of sampled plots were dried out separately by keeping it in hot oven until constant weight. Ultimately, the findings were summarized by calculating the average values from the data collected over two years.

The species *T. arjuna* was most adoptive in riverine ecosystem than the other species due to their ability to thrive under high moisture regime found abundant representing different diameter classes and density in paddy crop fields. Therefore, II and IIIrd investigations were conducted using this species only to evaluate the impact of different diameter classes and stem density (Stem counts) on paddy crop. Trees having diameter class of 10-40cm, 41–80 cm, 81–120 cm, and > 120 cm were marked at breast height and sample plots were taken close to the stem at 2m, 8m, 15m, and 25m aliened in East-West direction of transect line to quantify the yield loss pattern in paddy crop. Season of cropping, management practices and harvest timing were kept similar as mentioned in Ist experiment. Similarly, to understand the varying density of *T. arjuna* stems on paddy yield was determined considering 2, 4, 8 and 12 trees per plot of size 2000m² representing 10, 20, 40 and 60 trees ha⁻¹ respectively. Tree specific plot (*T. arjuna*) for these two experiments were chosen from the grid 8 and 10 considering 6 plots (2 plots/grid), and 3 individual tree stems for each diameter and density classes. Total 30 stem were chosen separately for these two investigations. For density class experiment, the size of the *T. arjuna* trees selected were in the size between 71-120cm diameter with a mean of 98.5cm at BH. Further the impact of varying DBH and density on paddy were quantified by laying out sample plots of similar size and distances as mentioned in species specific tree-crop interactions. The crop parameters under study were also assessed at the same distances (2, 8, 15, and 25m) from the reference field that had no trees, which was managed in the same way as the field with trees, located 200m away.

Measurement and data collection

Tree height, diameter at breast height (DBH), height of the lowest branch (HLB), crown depth and crown area were measured twice in 2020 and 2021 and the average values were provided in figure. Tree height was measured with a clinometer, while crown depth measured by deducting the HBL from the total tree height. The crown area was measured using standard formula (πr^2).

Statistical Analysis

We used multivariate analysis to analyse the effect of the species, distance, diameter classes and tree populations and their interactions between variables on paddy tillers, hills and yield using state Pro software. To determine the key factors influencing yield and paddy attributes and quantitative interrelationships backwards stepwise regression analysis was applied using the criteria of probability of $p < 0.05$. Furthermore, Tukey's Honestly Significant Difference (HSD) test was performed to determine significant differences between groups in the sample.

Results and discussions

The multivariate MANNOVA analysis of riverine agroforestry data shows that tree presence close and far from the crops varies significantly differed the growth and yield of paddy. The paddy yield showed significant difference to variables including tree species, diameter of trees, tree counts and its distances from the crop at $P < 0.05$.

4. 1. Effect of tree species on paddy growth and production

Tree morphological characteristics such as height, diameter, canopy depth and crown area and age differed species specifically and significantly (**Figure 3**). Among all the trees occurring in riverine agroforestry, *M. indica* was tall, large in diameter with broader crown and aged. Other trees such as *T. arjuna* and *T. tomentosa* showed slighter smaller 27m height with a crown expansion of 235-240 m² area. *B. monosperma* and *A. nilotica* had small heighted and lower crown depth and crown area than the other species resulted to form shadow in a relatively small area on paddy field. Paddy field without any tree showed highest yield of 5.91 t ha⁻¹ with the higher tillers and hill density as compared to the paddy field with trees ((**Table 1**). The paddy yield taken from different distances from the bund/ fields devoid trees was nonsignificant at $P < 0.05$.

We found a negative effect of various tree species in the paddy growth and yield at $P < 0.01$, except tillers which rendered nonsignificant result. Number of paddy tillers declined towards the proximity of tree whereas, increased with the increasing distance from the tree. This decline was 24.22%, 8.75% and 4.67% at 2m, 8m and 15m as compared to 25m distance from the tree trunk (**Figure 4**). When considering tree species *M. indica* had the greater effect in reducing the paddy tiller followed by *T. arjuna*, while the lowest impact was observed with *B. monosperma*. Similarly, the paddy hills were also negatively correlated with the increasing distances from the tree trunk. Results recorded the loss of 4 hills m² at the closest plot and 1.33 hills at the distance of 25m from the trees (**Table 2**). The loss was highest of 10.93% at 2m and 3.40% at farthest distance of the study. The presence of trees decreased the tillers and hills of paddy by 6.10 and 1.38% respectively as compared to paddy fields without trees (control plot). Species wise variation in the loss percentage of paddy hills was significant at $P < 0.01$. Results indicate that *M. indica* and *T. arjuna* trees had greater effect on the hills than other species.

Our study indicates the significantly negative impact of farm trees on paddy yields. The yield loss was highest towards the proximity of the trees. The grain yield of paddy ranged from 3.64 to 5.52 ton ha⁻¹ in our study which were obtained from 2m and 25m plots far from the tree trunk respectively (**Table 2**). On the other hand, grain yield reduced by 51.31% at 2m distance and 10.02% at 15m as compared to 25m distance from the tree trunk. Subsequently, the yield loss was 6.57% in fields with trees even far 25m from the trunk than the field devoid tree species. Significant variations on yield of paddy was observed due to presence of different tree species at varying distance from the tree trunk. Tree species *M. indica* could reduce the grain yield maximum by 72.96% followed by *T. tomentosa* (54.81%) and lowest of 43.35% at closest to crop. However, the grain yield losses were substantially lower with *A. nilotica*, *T. arjuna* and *B. monosperma* at 15 and 25m distances as compared to the same distances of other species of the study. The grain yield of paddy with *M. indica* was lowest (ranged 2.37 to 4.09 ton ha⁻¹) and highest (4.34 to 6.23t ha⁻¹) with *B. monosperma* at their closest and farthest plots of paddy fields. These data significantly differed at closure and far from the tree trunk which showed specific species variation in riverine agroforestry. Overall, the species such as *A. nilotica*, *B. monosperma* and *T. arjuna* exhibited less yield losses in paddy than the *M. indica* and *T. tomentosa*. Interactive effects of tree species and distance on paddy attributes under agroforestry practice was found nonsignificant at $P < 0.05$. The correlation between different tree species and their distance from the crop showed positive correlation for all the attributes, however its impact observed highest in paddy yield. Thus it can be said that irrespective of the tree species, the distance factor between tree- paddy was

more prominent and adverse for paddy yield (**Figure 5**). As the large tree with larger crown such as *M. indica*, and *T. tomentosa* tend to shade on large area in paddy field found more deleterious than the tree species which had small crown and short height.

Paddy requires strong sunlight for higher growth and yield than the other crops therefore, crop near tree line affected highest and its performed remain poor than the crop away from the tree or paddy crop with mono-cropping (Paula et al., 2018). Scordia et al. (2023) also compared Mediterranean agroforestry systems with treeless cropping systems and found that the majority of the studies identified shade as a cause of yield loss in field crops. Similar to our findings others also reported that the agroforestry of *Eucalyptus* tree had adverse effect on growth and yield attributes of crop due to its crown width and distance from the tree line (Khan et al., 2023; Koch et al., 2025). Under such conditions, the yield of the crop could be improved by manipulating the tree canopy, which further assist the crop growth component (Koch et al., 2025). Nadir et al., (2018) studied the relative performance of wheat crop with different shading intensities under *Eucalyptus* tree. Their findings highlights the decrease in photosynthetic rate, specific leaf weight and grain yield of wheat crop with the increase in shade duration (Yang et al., 2019). Moreover, Prasad et al. (2010) and Honfy et al. (2023) argued that the increase in grain yield with the increased distance from the tree line occurred due to increase in light intensity and decreased competition with the increased distance from the tree line between the tree roots. Bayala (2002) observed that the light competition is key for interactions between trees and crops. Tree species can reduce the amount of sunlight reaching crops and capture light depending upon tree factors viz. tree leaf area, leafing phenology, crown structure and crown management. The effect of *Prosopis cineraria* on yield of wheat crop due to distance has also been reported by Khan et al., (2023). This is the reason that the farmers pursued a regular tending operations to lesser the tree canopy and remove the exploitable diameter trees not for only the intermediate income from tree but also for the ease movements of farm equipment during farm activities (Koska et al, 2006; Pham et al., 2015; Miyagawa et al., 2017; Dumrongrojwatthana et al., 2020, Pardon et al., 2025, Koch et al., 2025). However, farmers have evolved management practices for reducing tree density, combining compatible species, and shoot pruning that contribute to control both above and below-ground competition (Namirembe et al., 2009). In riverine agroforestry, where copious amount of water is available to the tree species round the year, the tree flourish new leave and dense canopy round the year, therefore, tending and pruning operation become imperative to higher yield from the paddy crop.

4.2. Effect of diameter classes of trees

The varying diameter of trees occurring on levees of the paddy field were evaluated considering four diameter classes including 20-40cm, 41-80cm, 81-120cm and above 120cm (**Table 3**). Result reveals that the increase in tree diameter significantly reducing the paddy yields and its tiller, and hills. The higher tree diameter found to be more negative on paddy attributes than the less diameter levees trees. The mean tillers observed highest with tree diameter of 20-40cm and lowest with trees > 120cm diameter. In general, all the trees irrespective of diameter size had negative influence on the paddy yield parameters. However, the tiller loss was 19.07% with young trees with lesser diameter, whereas the losses increased to 26.48% with the largest diameter trees of the study (**Figure 6**). Similarly, the highest hills per meter recorded 41.59 and lowest 35.71 for youngest and oldest tree diameter respectively representing 16.46% loss in hill population when comparing between young and old tree diameters. The same trends also continued in paddy yield which obtained 5.63t ha⁻¹ with the presence of trees having 20-40cm diameter and 3.95t ha⁻¹ with trees diameters >120cm. The relative yield losses estimated due to higher diameter trees was found to be 42.53% than the losses with the lowest tree diameter. Moreover, the distance from the tree found to impact highest to the paddy yield which recorded significant difference at P<0.01. This resulted that the mean yield losses may be expected up to 37% with trees presence near to trees which may be declined up to 10.1%

with the increase of trees distance to the paddy crop. The DMR test also authenticated the influence of diameter classes on the paddy yield attributes which differentiated significantly at $P < 0.05$. Besides the effect of diameter classes on paddy yield parameters, the paddy crop close to the tree stem rendered less tillers, hills and yields than the paddy crops with increasing distances from the trees. The tiller formations in paddy were 12.50 m^2 at 2m trees proximity and 15 tillers m^2 at 25 from tree distances. Similarly, the hills number was ranged 36.17 to 41.75 m^2 at closest and farthest plots of the study. Paddy production was highest of 5.65 t ha^{-1} and lowest of 4.17 t ha^{-1} at the farthest tree distance of 25m and 2m sample plots respectively under varying diameter classes of the trees. Two way interaction between diameter class and distance was found nonsignificant at $P < 0.05$ which confirms that the tree and distance individually influence to the paddy yield when close to trees but its combined effect could not show any type of negative trends. Overall, the nonsignificant, negative correlation between DBH x tillers, DBH x hills of paddy, and DBH x yield of paddy ($R^2=0.0593$, 0.4614 and 0.5064 respectively) (**Figure 7**) also indicatives of the negative tree crop interface in paddy agroforestry systems. Reuse et al. (2025) and Pardon et al. (2018) observed that the tree height had a greater negative effect on crop yield in temperate climatic conditions. Other researchers also highlighted the light competition as a major factor playing a significant role and negatively influences the yields of annual crops (Pardon et al. 2018; Arenas-Corraliza et al. 2022) under agroforestry systems. The greater diameter tree develops large canopy with more height cast large shadow on crop for longer duration resulted to a higher yield loss at close proximity of the tree (Chauhan, et al. 2011). Crown shape of the trees and its size influence the degree of crop loss. Similar reports propounded by Kashyap et al. (2024) where paddy yield was decreased with the increase in tree diameter of *Gmelina arborea* plated in bund of the crop field. Thus need based regular pruning of tree branches can have positive impact in order to allowing more sunlight to paddy crop and substantially reduction to negative tree crop interaction. Luedeling et al., (2016) and Muthuri et al. (2009) also reported the effect of trees maize crop and indicated the benefits of pruning in reducing tree-crop competition. Moreover, harvesting of merchantable tree with greater diameter may be another solution for controlling the yield loss and economic benefit to the farmers.

4.3 Effect of tree stem counts on paddy attributes

Number of trees on levees and their influences on tillers, hills and yield of paddy under riverine agroforestry practices are summarized (**Table 4**). The results showed statistically significant data for paddy attributes when analysed considering tree population at the field and distances at $P < 0.05$. The mean number of tillers found highest 14.21 with the presence of two trees at 4m apart on levees while the lowest of 12.24 paddy tillers with the 12 trees occurring on levees of paddy agroforestry. The presence of tree augmented the tiller loss by 12.75% and 14.42% respectively for two and twelve trees maintaining at the farm levees (**Figure 8**). However, variation observed in the paddy tiller population under varying tree populations and with the tree distances from the paddy crops. The tree distance influenced the paddy tiller and reduced it by 19.23% when two trees present at the levees, whereas the tillers decreased by 37.85% with 12 trees when compared between the paddy at 2m and 25m distances from the trees. Similarly, the yield loss declined significantly with the increase in distance and remained 3.54% at the distance of 15m than the farthest distance of the study. Similar trends were also followed by the number of hills and yield of paddy. The paddy hills decreased by 3% with lowest tree population which magnified furthers up to 8.27% with highest trees numbers. The paddy crop close to the trees showed 11.06% yield loss, however, the negative impact was negligible going far away from the trees. The yield losses found 56.67% with two trees and 66.45% yield loss with the highest tree population growing just near levees trees. However, the paddy yield loss ranged 65% and 13.6% at plots close and far from the trees respectively. This loss was quantified up to 2.15 t ha^{-1} at closure plots than the crop growing at 25m distance from the trees. Two way ANOVA analysis showed nonsignificant results between tree number x distances. The negative correlation between the increasing number of trees and paddy

tillers, hills and yield (R^2 - 0.039, 0.337 and 0.156 respectively) (**Figure 7**) further prove the hypothesis that the increase in tree counts reduce the paddy yield through their growth attributes in riverine agroforestry practices. Our results concord with the findings of Khan and Chaudhry (2007) that indicated the increasing density of tree adversely affects the yield of crops under agroforestry. Vishwanath et al. (2000) and Kashyap et al. (2024) has evaluated the paddy yield under varying density of trees and reported that the higher stem number decline the paddy yield under tropical conditions. Reuse et al. (2025) also advocated the appropriate tree density based on observation that relative crop yields decrease with tree density. As tree density increases, the yield of arable crops can decrease (Honfy et al. 2023). On the other hand, more light penetration might be possible if trees are widely spaced with lower density.

Conclusion

The present investigation on tree-paddy interaction adjacent to river Lilager catchment where multiple tree species occurring naturally without any definite distance, and tree density in paddy crop fields clearly demonstrated the adverse impact on paddy growth characteristics and yield. Varying tree species had distinct impact on yield majorly based on crown size, and dimensions of the tree species. The shade effect of trees found to be the most important limiting factors for negative tree crop interaction. Larger the tree and denser the canopy causes more adversities on crop growth and yield aspects of paddy crop than the shorter and medium-small crown tree species. This factor can overcome with regular pruning of tree crown and harvest of exploitable diameter trees. It may become a regular source of farm income besides crop yield. In addition, higher tree density found to be deleterious for paddy production in a riverine ecosystem. The maintenance of appropriate tree counts between 10–20 ha⁻¹ to in paddy field allowing adequate sunlight and subsidise to reduce the yield loss. Conclusively, the selection of suitable indigenous tree species with small canopy size or vertical cylindrical canopy shape and their effective canopy management may maintain and or enhance the level the productivity and sustainability in paddy crop. Furthermore, more study need to conduct in a larger perspectives to authenticate and explore the species specific riverine agroforestry systems in other riverine area to confirm and encourage smart agriculture with nature based solutions.

Declarations

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Tables

Table-1: Growth and yield parameters of Paddy crop in a field devoid of any tree. The data shown are mean± SE of four replicates. (*Means within a row represented by different letters are significant at $p \leq 0.05$*).

Distance from levees (m)	No. of Tillers (pl ⁻¹)	No. of Paddy Hills (m ²)	Crop yields (kg/ha)
2m	14.5±0.56b	40.50±1.48b	5467.2±288.42b
8m	16.5±0.56a	41.33±0.67b	5770±215.65ab
15m	14.67±0.33b	40.17±1.25a	6078.7±171.17ab
25m	16.83±0.54a	41.50±1.18a	6348.6±112.73a
Mean	15.63±0.32	40.87±0.63	5916.1±118.64
F value	5.660	2.169	3.388
Significance (P)	0.006 (NS)	0.123 (NS)	0.038 (NS)

Table 2: Impact of different tree species on the Paddy crop growth and yields in riverine agroforestry practice prevailing along the river Lilagar catchments, Bilaspur, Chhattisgarh, India. (S1- *A. nilotica*, S2- *B. monosperma*, S3- *M. indica*, S4- *T. arjuna* S5- *T. tomentosa*). (*The data shown are mean± SE of four replicates. Means within a row presented by different letters are significant at $p \leq 0.05$*).

Tree Species	Tree distance from the crop field (m)				Mean
	2m	8m	15m	25m	
Tiller (pl ⁻¹)					
S1	11.10±1.0b	14.00±0.58a	14.00±0.50a	13.67±1.45a	12.70±0.56
S2	13.67±0.33b	13.67±0.33b	15.67±0.33a	15.33±0.88ab	14.58±0.36
S3	11±0.58b	13.33±1.2ab	13.33±1.45ab	15±0.50a	13.17±0.6
S4	11.67±1.45b	13.33±1.2ab	13.67±0.67ab	14.67±0.88a	13.33±0.57
S5	12.67±0.88bc	14.33±0.67b	14.67±1.76b	16±0.58a	14.42±0.58
Mean	12.02±0.70	13.73±0.55	14.26±0.54	14.93±0.64	13.64±0.36
Hills (m ²)					
S1	34.00±1.73ab	34.00±1.0ab	38.0±2.52a	37±1.53ab	35.75±0.93
S2	38.33±0.67b	39.33±0.67b	40±0.58ab	43±1.73a	40.17±0.68
S3	30.67±2.6b	33.33±1.2ab	34±1.15ab	35.33±1.45a	33.33±0.89
S4	37.67±2.6c	39.33±2.19bc	41±3.61b	43±1.73a	40.25±1.27
S5	42.33±2.67ab	43.33±0.67ab	43.33±1.76ab	44.67±1.45a	43.42±0.80
Mean	36.66±2.03	37.86±1.20	39.26±1.70	40.60±1.61	38.584±0.77
Yield (kg ha-1)					
S1	3340.1±471b	3673±290b	4827.3±244.29a	5068±294a	4227±263.90
S2	4346.5±9.73c	5030.7±121.3bc	5722±156.21ab	6230.7±377.74a	5332.5±232.84
S3	2369.5±116.9b	2889.7±367.62b	3321.3±394.8ab	4098.3±244.01a	3169.7±230.25
S4	3950.1±439.36c	5241.7±236.1ab	5713±369.49ab	6115.3±155.43a	5255±280.9
S5	4234.7±63.14c	5334.7±59.7b	5503.6±182.05b	6087.4±172.44a	5290.1±209.87
Mean	3648.18±230	4433.96±188	5017.44±245.30	5519.44±233	4654.46±217

Table 3: Diameter classes of *T. arjuna* impact on growth and yield of Paddy crop at varying distances from the tree base. (The data shown are mean± SE of four replicates. Means within a row presented by different letters are significant at $p \leq 0.05$).

Diameter Class	Tree distance from the crop field (m)				
	2m	8m	15m	25m	Mean
Tiller (pl⁻¹)					
10-40cm	14±0.58c	14.67±0.33bc	15.67±0.33ab	16.67±0.33a	15.25±0.35
40-80cm	12.67±0.33bc	13±0.58b	14.67±0.33a	14.33±0.67a	13.67±0.33
80-120	12±0.58bc	12.67±0.33bc	13±0.58b	14.67±0.33a	13.08±0.36
> 120	11.33±0.33b	12.00±0.33ab	13±0.58ab	14.33±1.2a	12.66±0.38
Mean	12.50±0.33	13.08±0.35	14.00±0.45	15.00±0.50	13.66±0.36
Hills (m²)					
10-40cm	38.7±1.58c	40.33±0.88bc	42.67±0.88ab	44.67±1.33a	41.59±0.86
40-80cm	38±2.58b	42±1.80ab	42.67±0.33ab	43.00±1.15a	41.41±0.39
80-120	35.67±0.33c	37.33±1.33b	40.00±1.15a	41.33±0.67a	38.58±0.73
> 120	32.33±1.36b	34±1.00ab	36.33±1.67ab	38.00±2.00a	35.17±0.86
Mean	36.17±01.88	38.41±0.90	40.41±0.83	41.75±1.40	39.19±0.70
Yield (kg ha⁻¹)					
10-40cm	4690±193.13c	5443.3±114.65b	5760±119.06b	6650.9±198.53a	5636±228.26
40-80cm	5002±107.35b	5304.6±72.92b	5757.6±92.31a	5940.1±221.35a	5462.5±125.68
80-120	3651.9±90.81c	4198.9±194.94bc	4754.4±211.28ab	5282.4±169.2a	4471.9±179.95
> 120	3161.5±173.7c	3644.8±88.4bc	4267.1±187.36ab	4740.5±282.79a	3953.5±199.22
Mean	4176.35±166	4597.9±112.50	5134.77±152.0	5653.47±188.0	4890.62±167.0

Table 4: Tree stem density of Paddy field and their effects on yield and other parameters in Paddy agroforestry existing along river Lilagar. (The data shown are mean± SE of four replicates. Means within a row represented by different letters are significant at $p \leq 0.05$).

Attribute	No. of stem	Tree distance from the crop field (m)				
		2m	8m	15m	25m	Mean
Tiller (pl ⁻¹)	2 stem	13±1a	13.67±0.88a	14.67±0.33ab	15.5±1a	14.21±0.37
	4 stem	12±0.58b	13.50±0.88ab	14.00±0.67ab	15±0.40a	13.62±0.42
	8 stem	12±1b	13.30±0.33ab	13.88±0.33a	14.00±0.67ab	13.29±0.39
	12 stem	9.67±0.67b	12.67±1.45a	13.3±2.08a	13.33±1.2a	12.24±0.74
	Mean	11.66±0.66	13.28±0.83	13.96±0.55	14.45±0.53	13.34±0.45
Hills (m ²)	2 stem	40±2.89ab	41.33±0.33ab	42.00±1.15a	42.33±2.19a	41.41±0.86
	4 stem	37.33±1.2ab	38.67±0.88ab	39.33±1.2a	40.00±2a	38.83±0.66
	8 stem	32.33±1.33b	34.67±1.88ab	37.67±0.88a	38.33±1.45a	35.75±0.88
	12 stem	32±2b	33±2.65b	37.00±2a	36.67±2.73a	34.66±1.08
	Mean	35.451±1.23	36.91±1.50	39.00±1.50	39.33±1.73	37.66±0.89
Yield (kg ha ⁻¹)	2 stem	4234±418.68b	5131.1±198.87b	5390±358.2ab	6633.6±649.05a	5347.2±318.79
	4 stem	3155.3±400b	3796.7±343.05b	4973±322.06a	5388±283.04a	4053.42±306.02
	8 stem	2998.3±150c	3622.1±132.99b	4510.1±341ab	5083.3±419.49a	4103.5±254.9
	12 stem	2893.2±138b	3595.2±167.95b	4419±449a	4815.7±453.79a	3930.77±281.28
	Mean	3320.2±265	4036.25±189.30	4823.02±340	5480.15±466	4414.90±270

Figures

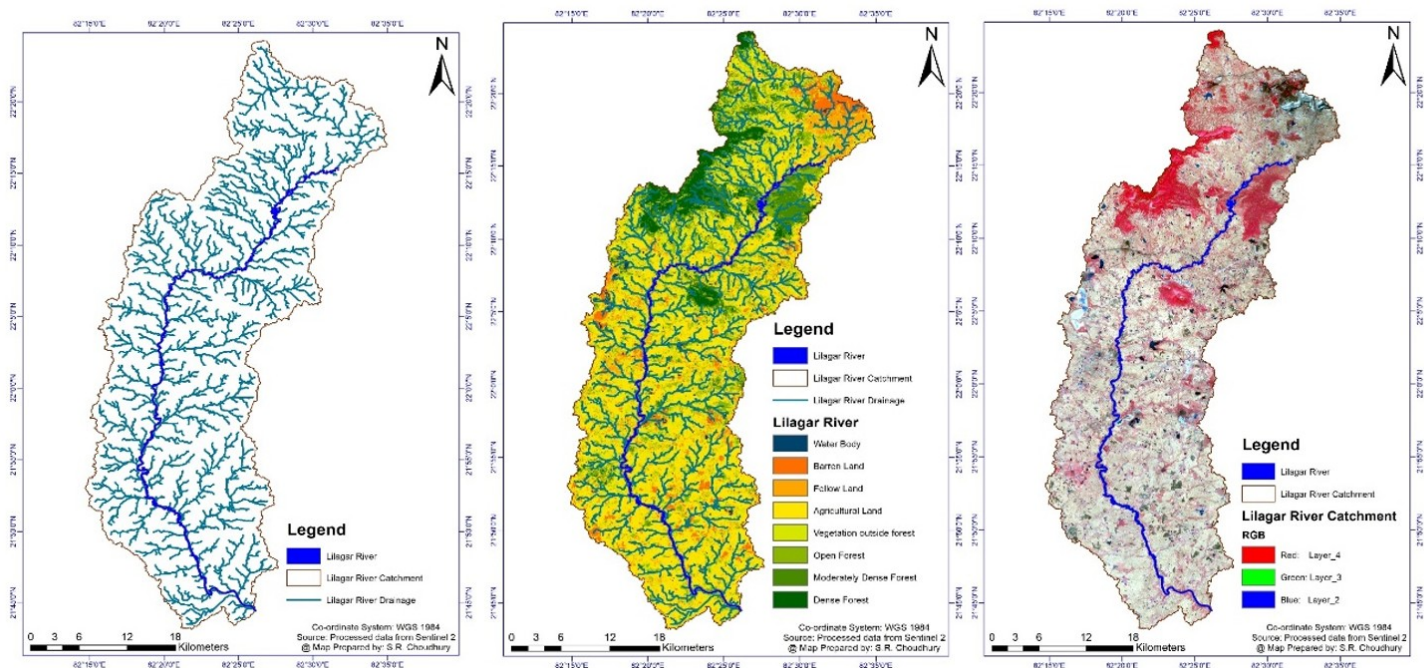


Figure 1

Study map showing the Lilagar river (A) Catchment and drainage (B) Vegetation, and river drainage (C) False colour composite map.

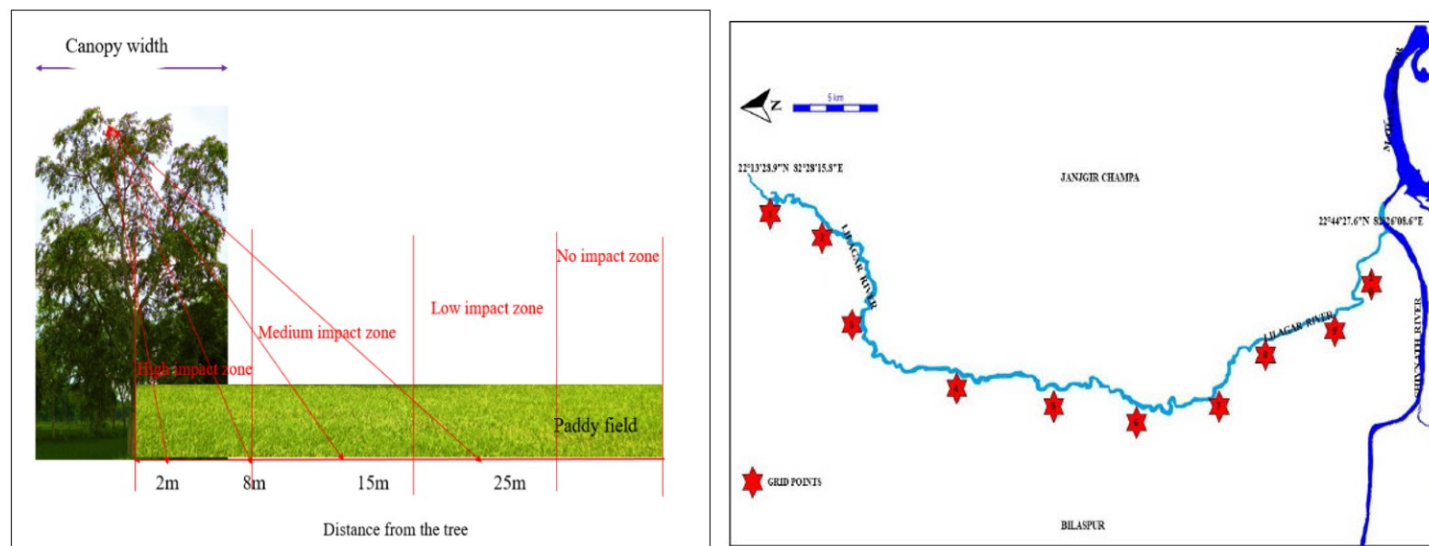


Figure 2

Diagrammatic representation of spatial arrangements in an agroforestry system, displaying tree line and sample plots at various distances from the tree and location of different grids along river stretches of Lilagar.

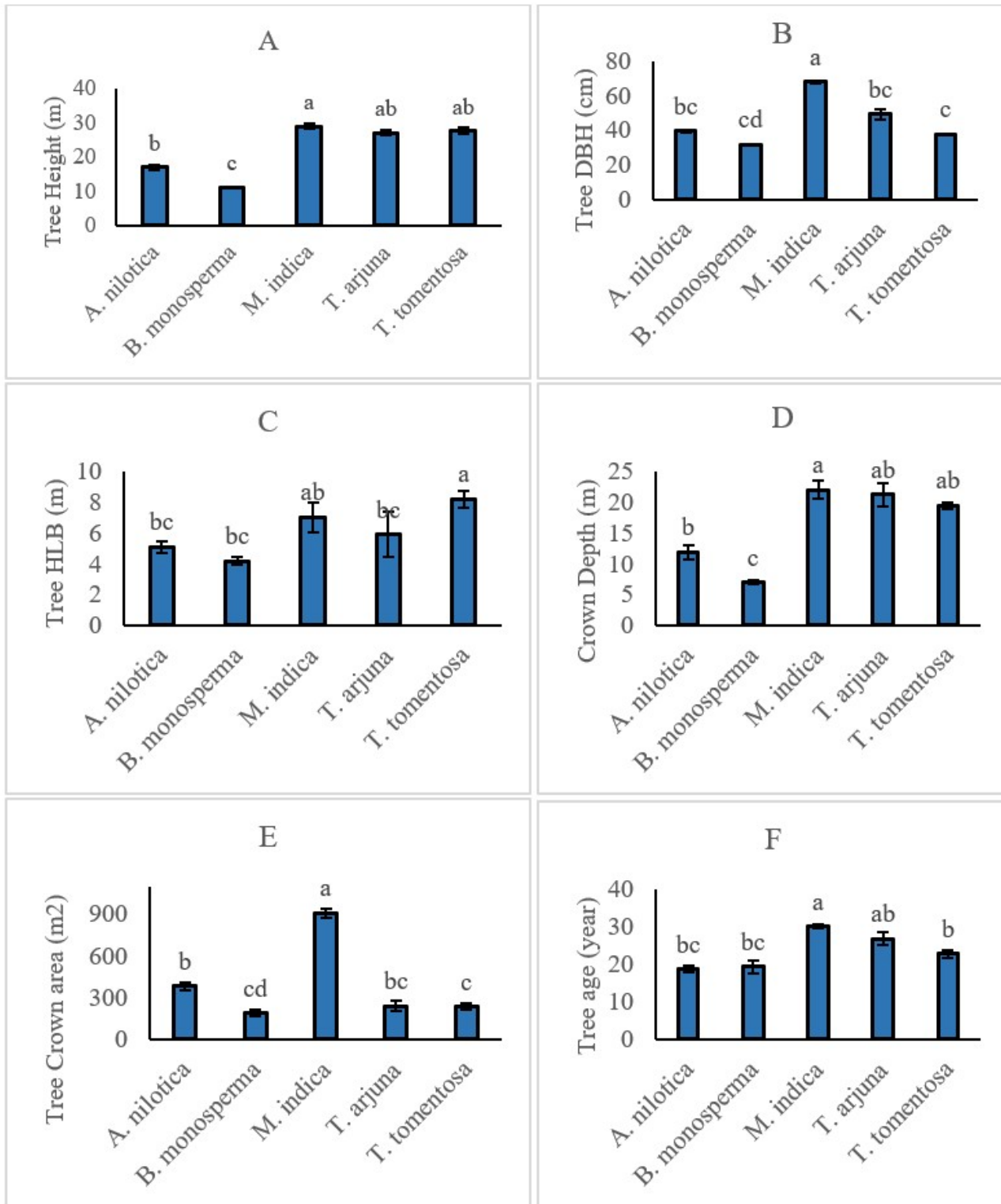


Figure 3

Morphological information of levees tree growing in Paddy based riverine agroforestry **A:** tree height (m), **B:** tree diameter at breast height (cm), **C:** height of lowest branch (m), **D:** crown depth (m), **E:** crown area (M²) and **F:** tree age (Years). The line on figure bar shows $\pm$ SE of the mean data. Different letters above the bar represents the significant difference at $p \leq 0.05$ as per DMR test. (DBH- Diameter at breast height, HLB- Height of lowest branch).

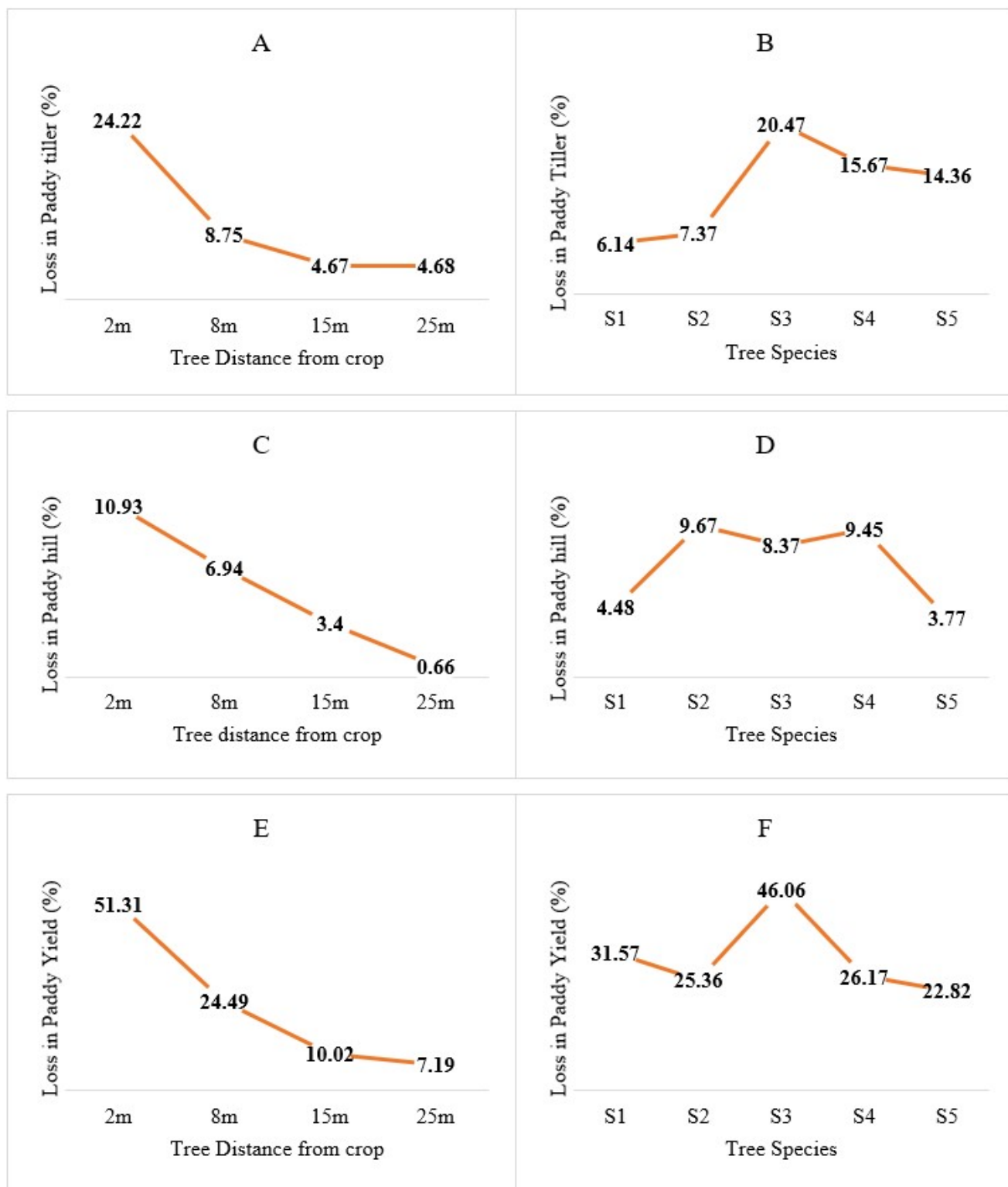


Figure 4

Loss pattern in Paddy attributes under the different tree species growing with Paddy crop in riverine agroforestry along Lilagar river, Bilaspur, Chhattisgarh, Central India. **A.** Tiller loss with tree distance from the tree, **B.** Tiller loss with different tree species (S1- *A. nilotica*, S2- *B. monosperma*, S3- *M. indica*, S4- *T. arjuna* S5- *T. tomentosa*), **C.** Hill loss with tree distance from the crop, **D.** Hill loss with tree species, **E.** Paddy yield loss with tree distance from the crop, **F.** Paddy Yield loss with different tree species.

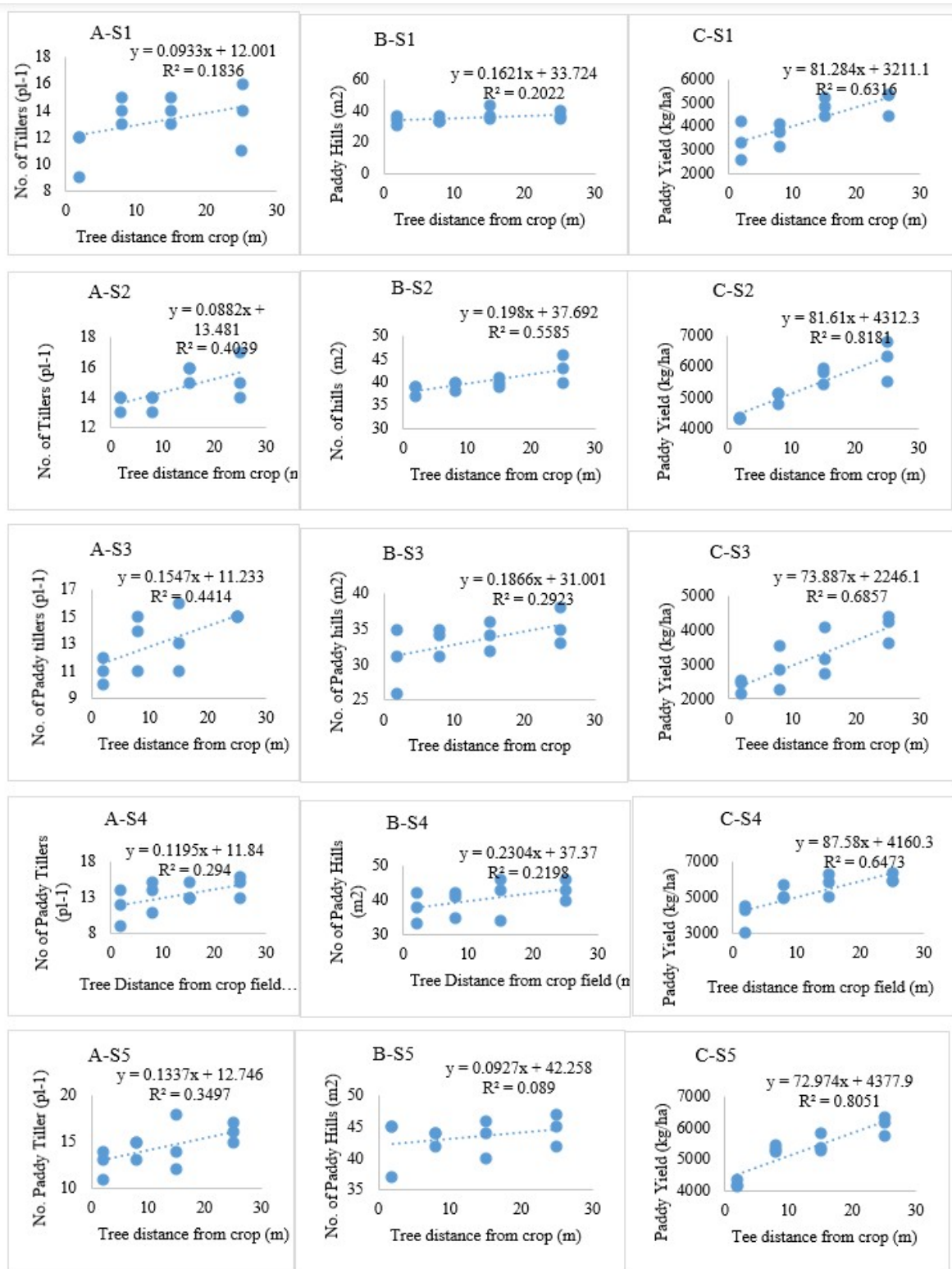


Figure 5

Correlation Coefficient (R^2) between **A.** tree species and Paddy tillers, **B.** tree species and Paddy hill and **C.** tree species and Paddy yield of riverine agroforestry under study. (**S1-A.** *nilotica*, **S2-B.** *monosperma*, **S3- M.** *indica*, **S4- T.** *arjuna*, **S5- T.** *tomentosa*).

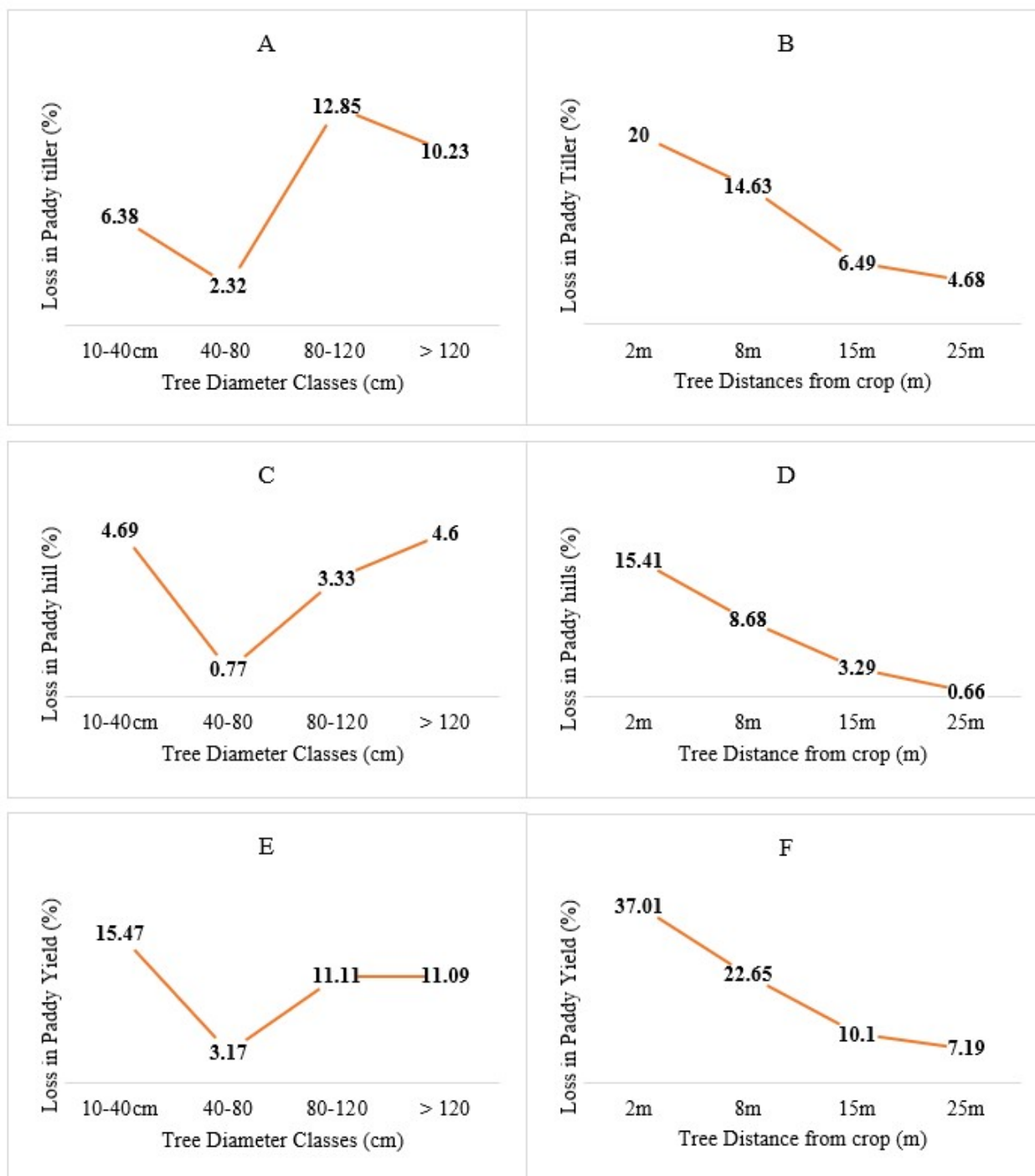


Figure 6

Loss pattern in Paddy attributes under *Tarjuna* of different diameter classes occurring in a riverine agroforestry adjacent Lilagar river, Chhattisgarh, Central India. **A.** Tiller loss with tree distance from the crop, **B.** Tiller loss with different diameter classes, **C.** Hill loss with tree distance from the crop, **D.** Hill loss with diameter classes, **E.** Paddy yield loss with tree distance from the crop, **F.** Paddy Yield loss with different diameter classes.

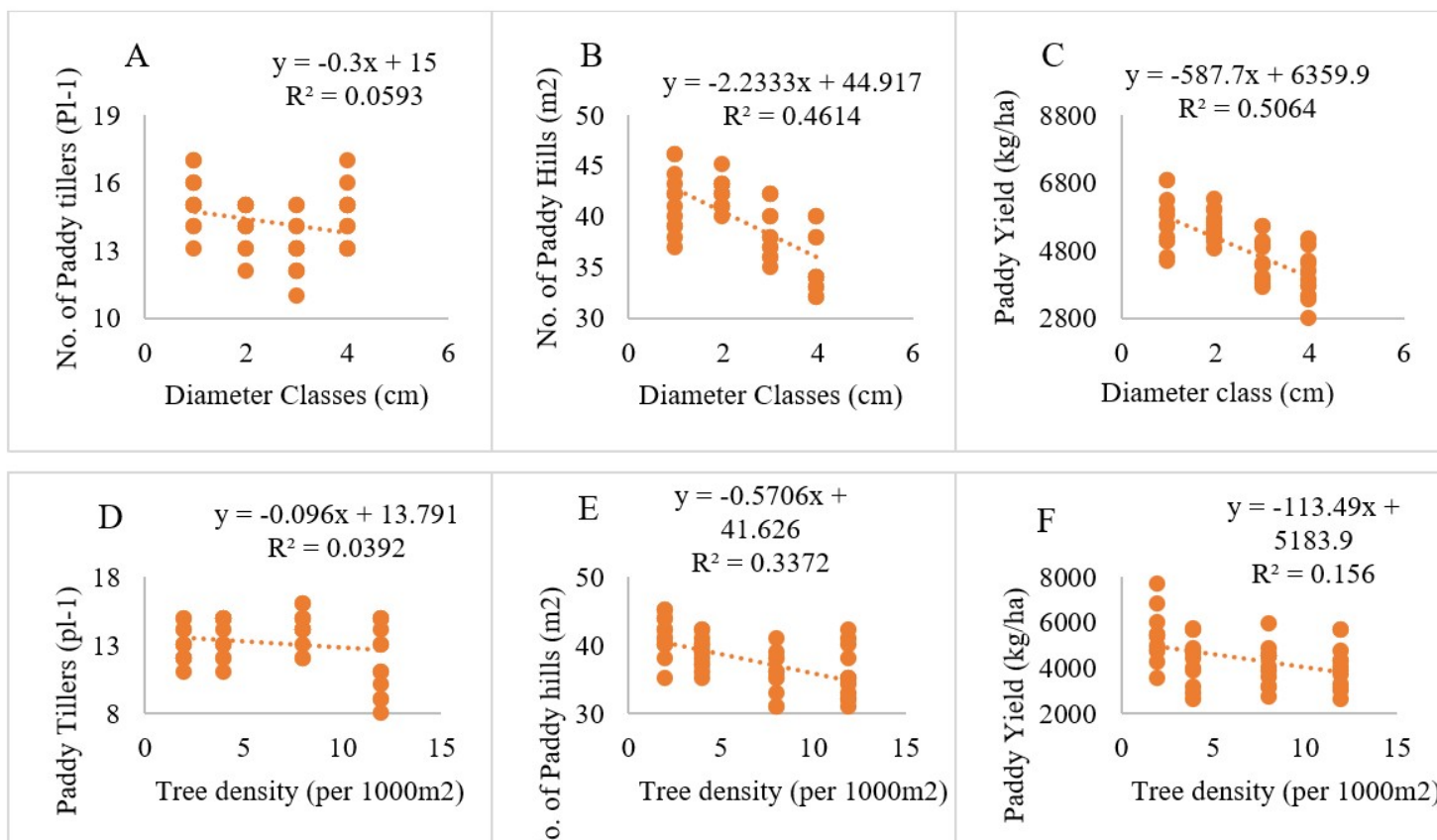


Figure 7

Correlation Coefficient (R^2) between **A.** Diameter classes x Paddy tillers, **B.** Diameter classes x Paddy hill and **C.** Diameter classes x Paddy yield **D.** Tree density x Paddy tillers, **E.** Tree density x Paddy hill and **F.** Tree density x Paddy yield in a riverine agroforestry under study.

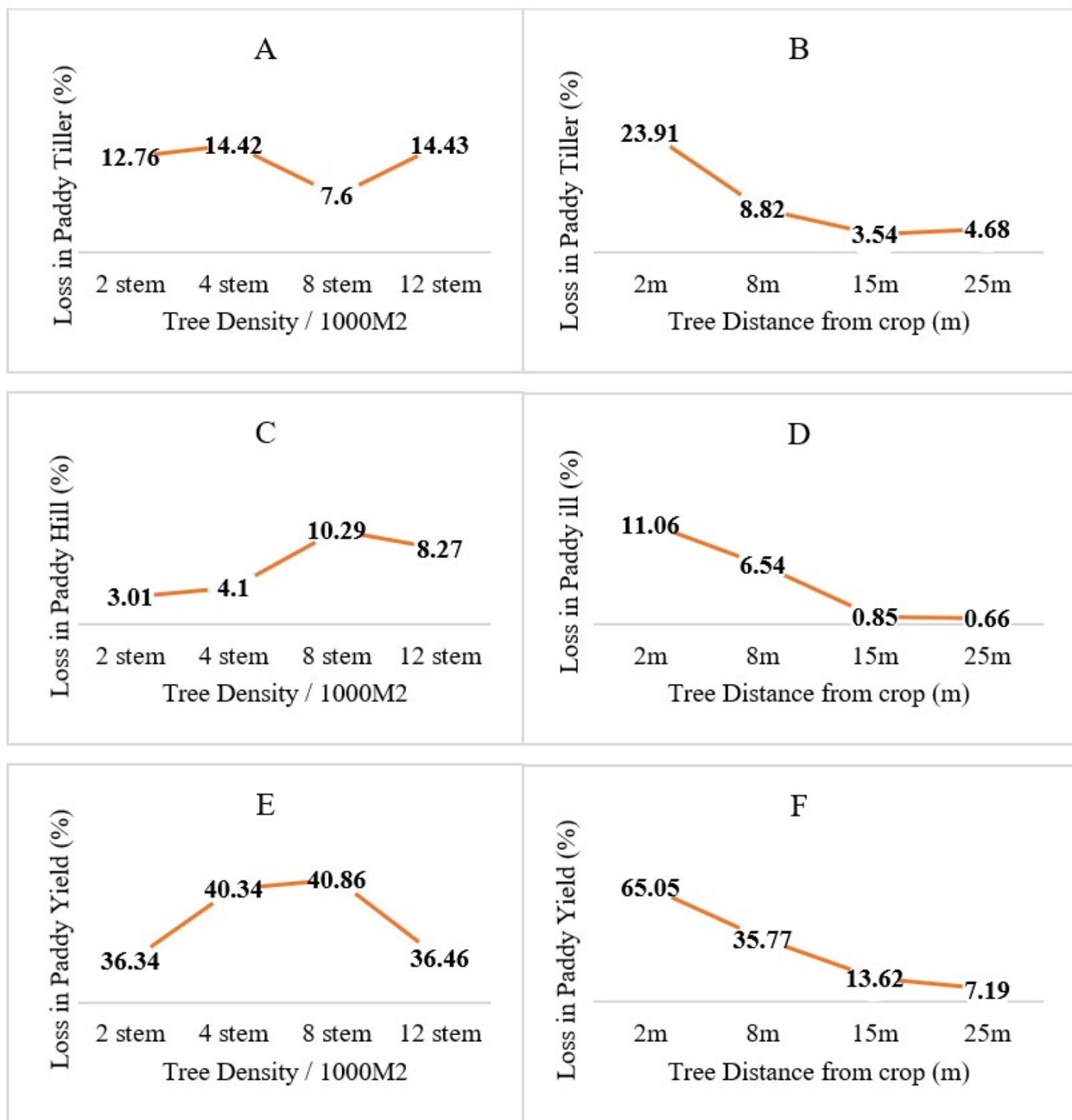


Figure 8

Loss pattern in Paddy attributes under the tree density (per 1000m² area) of *T arjuna* growing with Paddy crop in riverine agroforestry along Lilagar river, Bilaspur, Chhattisgarh, Central India. **A.** Tiller loss with tree density, **B.** Tiller loss with tree density, **C.** Hill loss with tree distance from the crop, **D.** Hill loss with tree density, **E.** Paddy Yield loss with tree density **F.** Paddy yield loss with tree distance from the crop.



Figure 9

Riverine agroforestry system showing *T. arjuna* maintained on farm levees in N-S orientation in paddy crop field adjacent to the river, Chhattisgarh, India.