Early Growth Dynamics and Spatial Occupation of Agricultural Land in an Alley-Cropping System

Elena Mihăilă[1], Mihăiță Bîtcă[1,3*], Adrian Tudora[1,4*], Elena Achim[1], Dorina Drăgan[1], Elena Partal[2], Elena Petcu[2]

[1]National Forestry Research-Development Institute "Marin Drăcea", 128 Eroilor Blvd., 077190 Voluntari, Ilfov County, Romania

[2]National Agricultural Research and Development Institute Fundulea, 915200 Fundulea, Călăraşi County, Romania

[3]Forestry Faculty, "Ștefan cel Mare" University of Suceava, 13 Universității Str., 720229 Suceava, Suceava County, Romania

[4]Faculty of Silviculture and Forest Engineering, Transilvania University of Brașov, 29 Eroilor Blvd., 500036 Brașov, Brașov County, Romania

[*]Corresponding authors. E-mail: bitcamihaita@gmail.com; tudoraadrian19@yahoo.com

ABSTRACT

This study analyzes the first five years of development (2021-2025) of an alley cropping agroforestry system established at NARDI Fundulea, Romania, evaluating the structural dynamics of *Ulmus pumila* L. across three contrasting planting variants. V1 comprised five 130-m rows with 8 m between trees and 50 m between rows, V2 comprised four rows with 4 m between trees and 75 m between rows, and V3 comprised three rows with 6 m between trees and 100 m between rows. The main objective was to monitor young-tree biometric development, particularly height, root collar diameter, crown expansion, and tree survival, and to quantify how the woody component progressively occupies space within the agricultural field.

All surviving trees were repeatedly measured. V3 consistently produced the largest individual trees and crowns; in 2025, mean crown area reached 18.02 m², compared with 11.28 m² in V1 and 10.13 m² in V2. However, canopy occupation at the system level showed a different pattern. Cumulative crown projection was greatest in V2, which also progressed most rapidly toward within-row canopy closure, showing that the configuration favouring individual tree development was not the same as that producing the greatest canopy occupation. Tree survival exceeded 91% in all configurations.

At this early stage, canopy expansion progressively modifies the spatial allocation of land and reduces the area directly available for cultivation, although the rate of physical occupation differs among variants. These results should not be interpreted as a direct measure of overall land-use efficiency. The study does not calculate the Land Equivalent Ratio (LER), because comparable long-term productivity data for both tree and crop components are not yet available. Instead, it establishes a structural baseline for future LER assessment and long-term monitoring of the balance between tree development, agricultural space, and system-level productivity.

Keywords: alley cropping system, crops, crown width toward the crop.

INTRODUCTION

The increasing occurrence of extreme climatic events and the gradual degradation of agricultural soils in lowland areas, resulting from intensive and continuous land cultivation, long-term use of chemical inputs, monocropping, and declining soil organic matter, call for an urgent transition towards more resilient production systems. In this context, agroforestry systems, including alley-cropping and tree-based shelterbelts are increasingly recognized for their potential to reconcile agricultural productivity with environmental protection and climate adaptation (Wolz and DeLucia, 2018; Xu et al., 2019; Mușat et al., 2021; Greene, 2025) with the provision of ecosystem services, including carbon sequestration (Oelbermann et al., 2004), biodiversity conservation (Boinot et al., 2019), and local microclimate regulation (Quinkenstein et al., 2009; Rivera-Pedroza et al., 2019; Donat et al., 2023). Although the benefits of mature agroforestry systems are widely documented (Jose, 2009; Burgess and Rosati, 2018), the structural

Received 10 July 2026; accepted 14 September 2026.

dynamics of the tree component during the early establishment phase remain insufficiently explored. This stage, encompassing approximately the first 5-10 years after establishment, is particularly critical from an agricultural management perspective because tree rows immediately occupy part of the agricultural area, while the woody component has not yet reached the structural development required to provide its full protective and microclimatic functions. Nevertheless, even relatively young tree rows can begin to modify local environmental conditions, and Chalupecká et al. (2026) highlighted the potential of integrating rows of trees within agricultural land to improve the local microclimate. As crowns expand, the relationship between individual tree growth, canopy continuity, retained cropped area, and potential ecosystem services changes continuously, highlighting the need for long-term monitoring of young agroforestry systems.

A key aspect in the design of alley-cropping systems is therefore the optimization of the spacing between tree rows. This variable determines the width of the agricultural alleys, the initial proportion of land allocated to the woody component, and the rate at which the field may become influenced by expanding tree crowns. Wider inter-row spacing (e.g., 100 m) preserves a larger cropped area and minimizes early competition for light and space, whereas narrower spacing (e.g., 50 m) may allow the protective network to become effective more rapidly, although it entails a greater initial allocation of land to the tree component (Van Lerberghe, 2017; Mihăilă et al., 2021; Greene, 2025). Within-row spacing is also important because it influences competition among neighbouring trees and the rate at which crowns become continuous along the row. Consequently, a configuration that favours rapid individual tree growth does not necessarily produce the greatest canopy occupation at the system level, as tree density and row arrangement modify the spatial expression of crown development.

The physical occupation of agricultural space by tree rows should not, however, be interpreted as an equivalent reduction in overall land-use efficiency. The Land Equivalent Ratio (LER) integrates the relative productivity of the tree and crop components and indicates the amount of land required under separate monocultures to obtain the same combined production as one hectare of an agroforestry system. Values above unity indicate a land-use advantage of the integrated system. Importantly, LER is not static but may vary throughout the lifetime of an alley-cropping system. During the first years after establishment, when trees occupy land but contribute little or no marketable production, LER may remain below unity. As the woody component develops, the balance may change because trees increasingly contribute directly to system productivity and may also exert beneficial effects on associated crops (Xu et al., 2019). This temporal dimension has been demonstrated in empirical studies. In apple-based alley cropping, LER values were below unity before trees began to bear fruit and exceeded unity afterwards, showing that land-use efficiency can change substantially as the woody component develops (Xu et al., 2019). In temperate tree-strip systems, LER also varied among sites and design scenarios according to the relative proportions and productivity of tree and crop components (Seserman et al., 2019). These findings indicate that a single-year assessment may not adequately represent the long-term efficiency of an agroforestry system and that LER should ideally be evaluated over the entire lifespan of the system.

Alley-cropping systems consist of agricultural crops grown between rows of trees or other linear woody elements established within agricultural land, with the distance between tree rows varying according to the objectives defined at system establishment. In Romania, alley cropping represents a relatively new paradigm that is still at an early stage of testing. Unlike conventional shelterbelts, whose primary role is to reduce wind speed at the landscape scale, alley-cropping systems involve a denser integration of trees within the productive agricultural area and require active management of tree-crop interactions and competition for resources.

The present study analyses the biometric and spatial development of an experimental alley-cropping system established in 2021 at the National Agricultural Research and Development Institute, Fundulea, Romania. The experiment includes three inter-row spacing configurations of 50, 75, and 100 m. The study focuses on the spatial dynamics of the woody component during the first five growing seasons, with particular emphasis on horizontal crown projection area, frontal crown area, canopy continuity, and the progressive occupation of agricultural space.

The early development of the Fundulea alley-cropping experiment was previously reported by Tudora et al. (2022), who described establishment conditions and tree growth during 2021-2022. The present study extends the observation period to 2025 and shifts the analytical focus from initial establishment to longitudinal growth trajectories, crown expansion, tree survival, and system-level canopy occupation. LER was not calculated because comparable long-term productivity data for both the tree and crop components were not available. Instead, the study addresses an earlier and necessary step by quantifying the structural development and spatial occupation of the woody component that will shape future tree-crop interactions and provide a baseline for subsequent assessments of land-use efficiency.

Accordingly, the main objective of this study was to document the spatial footprint and early structural development of the tree component within this long-term experiment to assess its initial impact on usable agricultural area and its emerging potential for microclimate modification. Specifically, the study aimed to: (i) compare the 2021-2025 trajectories of tree height, root collar diameter, and crown development; (ii) quantify cumulative crown projection using a complete census of surviving trees and the actual area of each experimental configuration; (iii) assess progression towards within-row canopy closure; and (iv) evaluate tree survival during the first five growing seasons. The research hypothesis is that, although inter-row spacing would not result in significant differences in individual tree growth rates during the first five years, spatial configuration would determine different levels of land occupation and distinct patterns of canopy coverage, with implications for the future development of microclimatic protection and drought-adaptation functions.

MATERIAL AND METHODS

Study site and experimental design

The experiment was established in spring 2021 at the National Agricultural Research and Development Institute (NARDI) Fundulea, Călăraşi County (Latitude: N 44.26387; Longitude: E 26.30267), in southeastern Romania, at an elevation of approximately 67 m above sea level. The site is located in the eastern Romanian Plain, in the transition area between the Vlăsia Plain and the southern Bărăgan. The mean annual temperature is approximately 10.9°C, and the mean annual precipitation is approximately 510 mm. The soil is a cambic chernozem. A detailed description of the site, establishment procedures, protective tubes, uncultivated tree strips, and early development of the experiment was provided by Tudora et al. (2022).

The experimental alley-cropping system comprised three contrasting variants of *Ulmus pumila* L. V1 included five 130-m-long tree rows, with 8 m between trees within rows and 50 m between rows. V2 included four 130-m-long rows, with 4 m between trees and 75 m between rows. V3 included three 130-m-long rows, with 6 m between trees and 100 m between rows (Figure 1). Due to the farm's annual crop rotation, the crop species adjacent to a given tree row varied across years and were not considered a static feature of the system layout.

Tree measurements

At establishment, the tree rows were allocated an approximately 1 m wide uncultivated strip (total strip width). The seedlings were small, protected by tubes, and agricultural operations were conducted as close as practically possible to the tree rows to minimize the loss of cropped land. As the trees developed, the effective uncultivated strip was progressively widened and reached approximately 2 m in total width by 2025. For the phase examined here, this width adequately represents the area directly withdrawn from cultivation under the actual farm-management practice. To provide a transparent estimate of the direct effect of tree-row management on usable agricultural area, two reference strip-width scenarios were calculated: the initial 1-m strip and the approximately 2-m strip reached by 2025 (Table 1). For each variant, uncultivated agricultural area was calculated as the number of rows × row length × strip width.

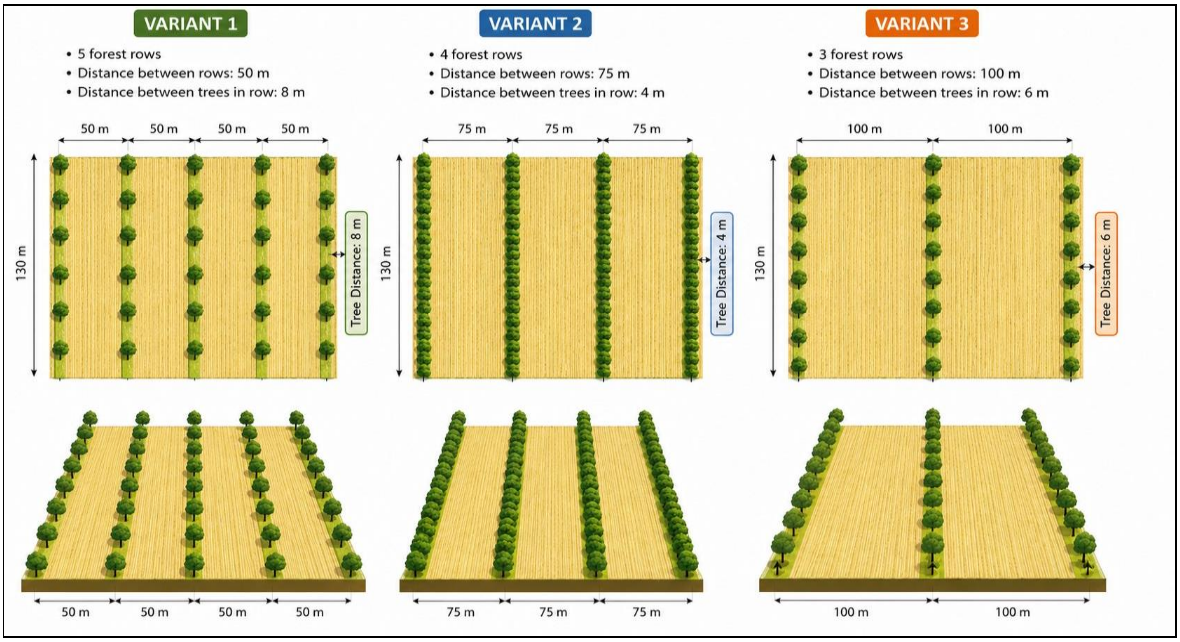

Figure 1. Experimental layout of the three alley cropping variants at NARDI Fundulea

These scenario-based calculations quantify only the land physically excluded from cultivation by the managed tree strips. They do not represent the wider area potentially influenced by shade, roots, wind reduction, or other microclimatic effects.

Table 1. Scenario-based direct occupation of agricultural land by the managed tree strips

Variant	Total row length (m)	Uncultivated agricultural area (m²)	
		At 1 m strip (m²)	At 2 m strip (m²)
V1	650	650	1300
V2	520	520	1040
V3	390	390	780

All living trees in the experiment were measured; therefore, the dataset represents a full inventory of surviving trees. Total height was recorded at the end of each growing season from 2021 to 2025. Root collar diameter and crown dimensions were assessed from 2022 to 2025. Crown projection was measured in two perpendicular directions: along the tree row and perpendicular to the row, toward the adjacent agricultural crop. Particular attention was given to crown width toward the crop, as this directly measured variable indicates the tendency of the woody component to expand beyond the managed uncultivated strip into the agricultural space. Crown width toward the crop and managed strip width were treated as distinct indicators: the latter represents land directly excluded from cultivation, whereas the former reflects structural expansion of the tree component and does not necessarily imply an equivalent loss of cropped area. Tree survival was calculated as the number of living trees recorded in 2025 divided by the number reported in 2021 × 100. Mean individual crown area was used to characterize crown development, while crown width toward the crop was used as the principal measured indicator of structural expansion toward the agricultural component. A within-row canopy closure index was calculated as mean crown width divided by within-row tree spacing × 100. Values approaching 100% indicate that mean crown width along the row approaches the distance between neighboring trees and that the row is progressing toward a continuous canopy strip.

Statistical analysis

Descriptive statistics were calculated for each variant and measurement year. Changes over time were analyzed using linear mixed-effects models to account for repeated measurements of individual trees and their grouping within rows (Bates et al., 2015). Variants, year, and the variant × year interaction were included as fixed effects. Random intercepts were included for rows nested within variant and for individual trees nested within rows, to account for variation among rows and repeated measurements of the same trees. The contribution of variant, year, and their interaction was assessed using likelihood-ratio tests based on comparisons of nested models fitted by maximum likelihood. Crown area was square-root transformed before modelling to improve model residuals. For the final measurement year, pairwise comparisons among variants were additionally performed using Welch's t-tests, with Holm adjustment for the three comparisons within each trait (variable). Statistical significance was accepted at $p < 0.05$.

RESULTS AND DISCUSSION

Tree growth and crown development

Tree survival from 2021 to 2025 was 91.2% in V1, 93.9% in V2, and 95.4% in V3 (Table 2). More than 91% of the initial trees remained in all configurations.

Table 2. Tree numbers and survival between 2021 and 2025

Variant	Trees in 2021	Trees in 2025	Tree survival (%)
V1	80	73	91.2
V2	131	123	93.9
V3	65	62	95.4

Tree height increased progressively in all variants between 2021 and 2025, while root collar diameter showed a similar upward trend from 2022 to 2025 (Figures 2 and 3).

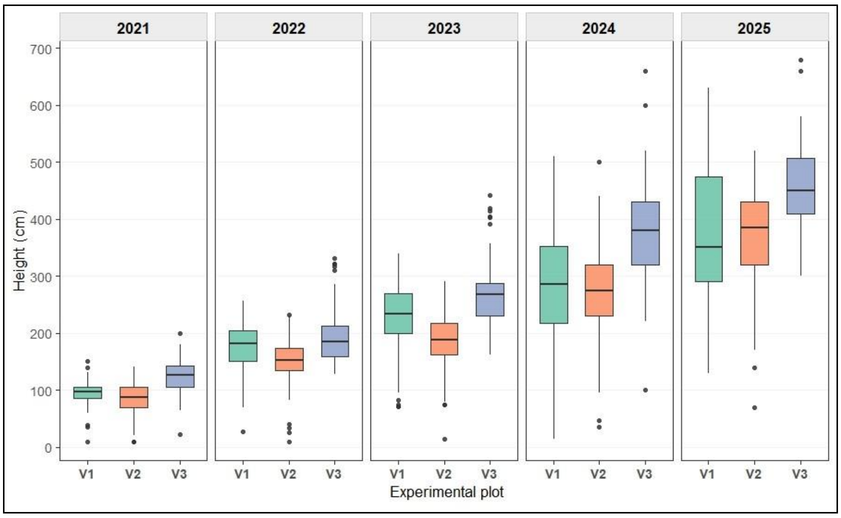

Figure 2. Distribution of tree height across variants during the monitoring period

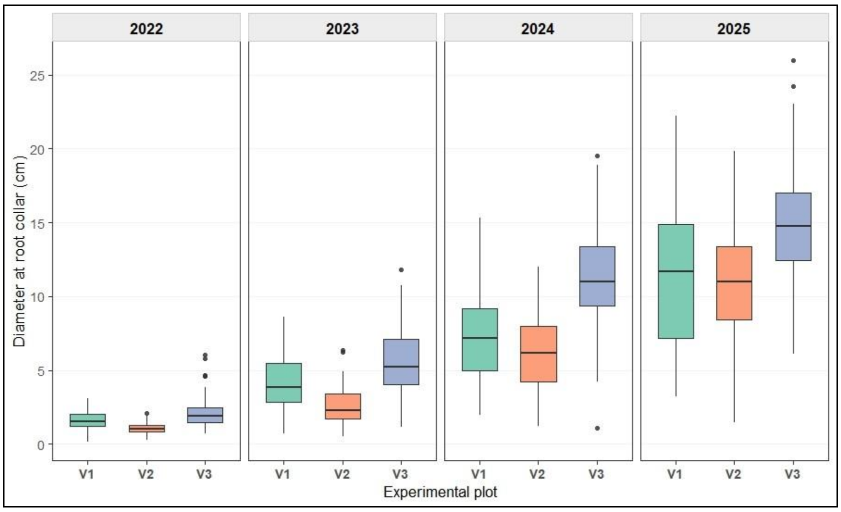

Figure 3. Distribution of root collar diameter across variants during the monitoring period

V3 maintained the highest mean values throughout the monitoring period. By 2025, mean height reached 457.3 cm in V3, compared with 381.4 cm in V1 and 362.9 cm in V2. Root collar diameter showed the same general ranking, with the strongest development in V3 and more similar final values in V1 and V2. Linear mixed-effects models showed significant effects of variant, year, and their interaction for both tree height and root collar diameter (Table 3). In 2025, V3 differed significantly from both V1 and V2 for both traits after Holm adjustment (all adjusted $p < 0.001$), whereas V1 and V2 did not differ significantly (adjusted $p = 0.235$ for height and $p = 0.184$ for root collar diameter).

Table 3. Likelihood-ratio tests for the effects of variant, year, and their interaction on tree growth and crown development

Trait (Variable)	Effect (Tested factor)	LR	df	p
Tree height	Variant	10.26	2	0,0059
	Year	1971.20	4	< 0.001
	Variant x year	89.21	8	< 0.001
Root collar diameter	Variant	11.87	2	0,0026
	Year	1535.13	3	< 0.001
	Variant x year	117.51	6	< 0.001
Crown area	Variant	15.03	2	0.0005
	Year	1545.40	3	< 0.001
	Variant x year	75.76	6	< 0.001
Crown width toward the crop	Variant	16.25	2	0.0003
	Year	1307.55	3	< 0.001
	Variant x year	43.71	6	< 0.001
LR - likelihood-ratio statistic; df - degrees of freedom; p - probability value.				

Mean crown area increased strongly in all variants and showed the clearest structural differentiation (Figure 4). In 2025, mean individual crown area reached 18.02 m² in V3, 11.28 m² in V1, and 10.13 m² in V2. Although V2 had the smallest mean individual crown area, its closer 4 m within-row spacing was associated with earlier progression toward contact between neighboring crowns. Thus, V3 showed the greatest individual crown development, but this ranking did not fully describe the spatial implications of planting design.

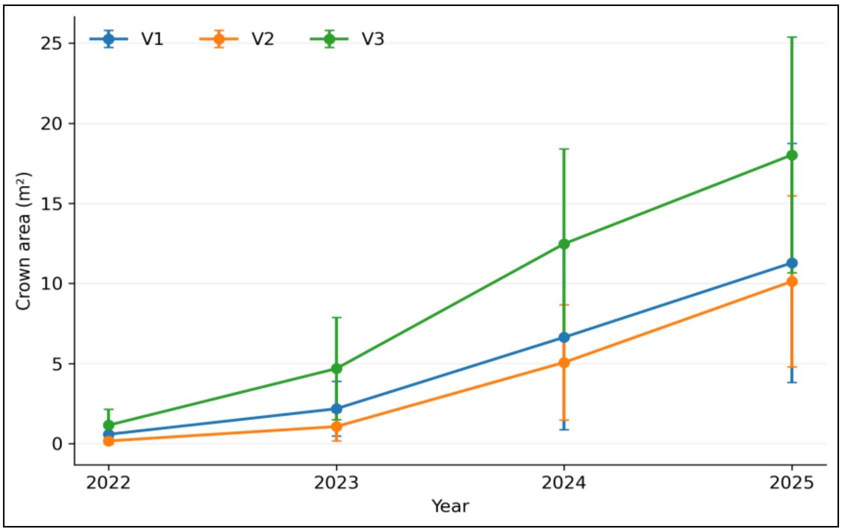

Figure 4. Mean crown projection area dynamics in the three planting variants

Crown width toward the agricultural crop, the dimension most directly relevant to structural expansion into the cropped space during this young phase, also increased in all variants, with the greatest final values in V3 (Figure 5).

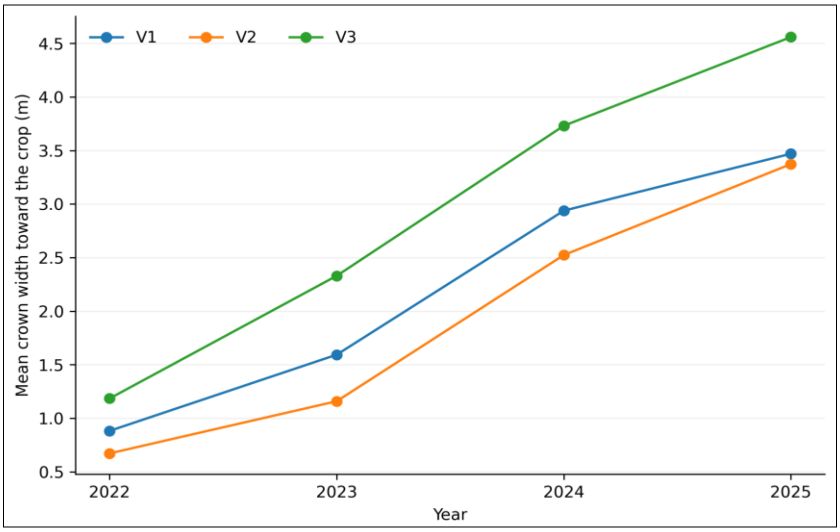

Figure 5. Mean crown width toward the adjacent agricultural crop in the three planting variants

Linear mixed-effects models showed significant effects of variant, year, and their interaction for both crown area and crown width (Table 3). In 2025, V3 differed significantly from V1 and V2 for both traits (variables) (all Holm-adjusted $p < 0.001$), while V1 and V2 did not differ significantly (adjusted $p = 0.248$ for crown area and $p = 0.585$ for crown width).

Within-row canopy closure showed a different pattern from individual crown development. In 2025, mean crown width along the row was 3.67 m in V1, 3.55 m in V2, and 4.82 m in V3. Relative to the corresponding within-row tree spacings of 8, 4, and 6 m, these values resulted in canopy closure indices of 45.9%, 88.6%, and 80.4%, respectively. Thus, although V3 showed the greatest individual crown development, V2 had progressed furthest toward within-row canopy continuity by 2025.

Spatial and structural evolution of the single tree row

Under the initial 1-m strip scenario, the directly uncultivated area was estimated at

650 m² in V1, 520 m² in V2, and 390 m² in V3. At an approximately 2-m strip width, corresponding to the effective width reached by 2025, these areas increased to 1300, 1040, and 780 m², respectively. Thus, widening from 1 to 2 m represented an additional direct exclusion from cultivation of 650 m² in V1, 520 m² in V2, and 390 m² in V3. These values describe the management-related occupation of agricultural land and should not be interpreted as the total area influenced by the trees.

Across all trees, mean crown width toward the agricultural crop increased from 2.95 m in 2024 to 3.69 m in 2025. In 2025, variant means were 3.47 m in V1, 3.37 m in V2, and 4.56 m in V3. Thus, by the end of the young phase, structural crown expansion toward the crop was already substantially greater than the approximately 2-m total width of the managed uncultivated strip. This contrast does not imply that the land beneath the crown projection was removed from cultivation: farmers continued to cultivate as close as practically possible to the tree row in order to minimize loss of productive land. Crown width was significantly affected by variant (LR = 16.25, df = 2, $p = 0.0003$), year (LR = 1307.55, df = 3, $p < 0.001$), and their interaction (LR = 43.71, df = 6, $p < 0.001$). In 2025, V3 differed significantly from V1 and V2 (Holm-adjusted $p < 0.001$), while V1 and V2 did not differ significantly.

The results reveal two complementary dimensions of spatial development in young alley-cropping systems. The first is the direct occupation of agricultural land by the managed tree row. The second is the progressive structural expansion of the crowns toward the crop. These dimensions should not be confused: row widening represents land physically excluded from cultivation, whereas crown expansion describes increasing tree influence over agricultural space without necessarily removing that land from production. The management history of the Fundulea experiment is particularly relevant in this respect. At establishment, the approximately 1 m total strip width was sufficient because the seedlings were small and protected in tubes, and farmers cultivated as close as practically possible to the tree rows to avoid unnecessary production losses. As the trees developed, maintaining such a narrow strip became increasingly impractical, and the effective strip widened to approximately 2 m in total width by 2025. Throughout this early developmental stage, the mean crown width on the crop side increased from 2.95 m in 2024 to 3.69 m in 2025. The area directly withdrawn from cultivation therefore remained smaller than the space occupied by crown expansion toward the crop. This is a central distinction of the study: managed strip width represents a direct loss of cropped area, whereas structural crown occupation may extend over land that remains under cultivation. During the early stage phase examined here, crown expansion toward the agricultural crop was considered particularly relevant from a management perspective because it directly reflects the increasing spatial interaction between the forest and agricultural components. As the system matures, along-row crown development and eventual canopy continuity may become increasingly important for providing shelter, shade, and microclimatic regulation, which are recognized functions of agroforestry systems (Veldkamp et al., 2023; Koch et al., 2025). The scenario calculations show that the direct impact on usable agricultural area depends strongly on total row length. V1, with five rows, required the largest directly uncultivated area, whereas V3, with three rows, required the smallest. This is an important design implication: increasing the number of rows may accelerate the spatial presence and potential functional influence of the woody component, but it also increases the area that must be permanently or progressively withdrawn from cultivation.

Crown expansion toward the agricultural crop provides a second and directly measured perspective, while also highlighting a potential management challenge, as lateral crown growth may eventually require pruning, a practice commonly used in alley-cropping systems to limit crop shading and competition (Ivezic et al., 2021; Maitra et al., 2025). V3 produced the greatest individual crown expansion toward the crop, while V2, characterized by the closest within-row spacing, progressed most rapidly toward canopy continuity. Thus, the variant that minimized direct row area was not necessarily the configuration with the least structural expansion toward adjacent crops. This distinction strengthens the central finding that spatial arrangement influences individual growth, row continuity, and agricultural-space occupation in different ways. The strong individual development of V3 cannot be attributed exclusively to spacing. This accelerated growth may have been driven by local spatial context or initial seedling size advantages, given that V3 was the first variant to be planted. The variants should therefore be interpreted as contrasting field configurations rather than as a fully factorial spacing experiment.

The reduction in directly cultivated area should not be interpreted as an equivalent reduction in overall land-use efficiency, as this depends on the combined productivity of the tree and crop components and can be assessed using the Land Equivalent Ratio (LER) (Xu et al., 2019; Honfy et al., 2023). LER integrates the productivity of the woody and crop components relative to their respective monocultures and may remain above unity even when the area available for annual crops is reduced. The present study does not calculate LER because comparable long-term productivity data for both components were unavailable. However, the direct strip-area scenarios and the measured crown expansion toward the agricultural crop establish two structural dimensions that should be incorporated into future assessments of land-use efficiency.

Future monitoring should therefore record effective strip width systematically, preferably annually and separately for each row. Crop yields should also be measured at defined distances from the tree rows, following approaches used in previous alley-cropping studies (Majaura et al., 2024; Reuse and Langhof, 2025). This would allow the direct loss of cropped area to be separated from the wider zone of tree influence and would provide the data required to determine whether structural expansion is compensated by gains in tree production, crop performance, or ecosystem services.

The three variants represent different spatial and management patterns. V1 has the greatest total row length and therefore the largest direct strip-area requirement; V2 combines high tree numbers with rapid progression toward canopy continuity; and V3 has the smallest total row length but the strongest individual tree and crown expansion toward the agricultural crop. The appropriate design therefore depends on the balance sought among direct preservation of cropped area, rapid formation of a continuous woody strip, and individual tree development.

The 1 m and 2 m strip widths should be regarded as reference estimates based on field management observations rather than as a measured annual time series. The variants also differ simultaneously in within-row spacing, inter-row distance, number of rows, and local spatial context. The effects of any single spacing factor therefore cannot be isolated. Annual crop rotation further means that crop identity is not a fixed property of a variant. The results should therefore be interpreted as a comparison of the development patterns observed in the three experimental variants.

CONCLUSIONS

During the first five growing seasons, *Ulmus pumila* showed good establishment and sustained development in all three alley-cropping configurations, with tree survival ranging from 91.2% in five-row configuration to 95.4% in three-row configuration. By 2025, three-row configuration showed the strongest individual tree development, reaching a mean height of 457.3 cm, compared with 381.4 cm in five-row configuration and 362.9 cm in four-row configuration, and a mean crown area of 18.02 m², compared with 11.28 m² in V1 (five-row configuration) and 10.13 m² in V2 (four-row configuration).

The direct area excluded from cultivation depended primarily on total tree-row length and managed strip width. Under the reference 1 m total strip-width scenario, the directly uncultivated area was 650 m² for the five-row configuration (V1), 520 m² for the four-row configuration (V2), and 390 m² for the three-row configuration (V3). At the approximately 2 m strip width reached by 2025, these values increased to 1,300, 1,040, and 780 m², respectively. At the same time, mean crown width toward the agricultural crop increased from 2.95 m in 2024 to 3.69 m in 2025, reaching 4.56 m in V3. Thus, crown expansion already extended beyond the managed tree strip, although this structural occupation should not be equated with an equivalent loss of cultivated land because agricultural operations continued beneath and adjacent to the expanding crowns wherever practicable.

The three configurations therefore represent different trade-offs between tree development and agricultural-space occupation. V1 required the largest directly uncultivated area because of its greater total row length, V2 showed the greatest cumulative crown projection at the system level and progressed most rapidly toward within-row canopy continuity, whereas V3 combined the smallest direct strip-area requirement with the strongest individual tree and crown development. Thus, the configuration favouring individual tree development was not the same as that producing the greatest canopy occupation at the system level. These results demonstrate that direct strip occupation, individual crown expansion, cumulative canopy occupation, and within-row canopy continuity represent complementary rather than interchangeable dimensions of spatial development in young alley-cropping systems.

The present results describe the structural development of the system rather than its overall land-use efficiency. Continued monitoring of effective tree-strip width, crown development, crop yields at defined distances from the tree rows, and microclimatic conditions will be necessary to determine whether the progressive occupation and influence of the woody component are compensated by gains in crop performance, tree production, and ecosystem services. Such data will allow the area directly excluded from cultivation to be distinguished from the broader area influenced by the trees and will provide a more complete assessment of the long-term performance of the alley-cropping system.

ACKNOWLEDGEMENTS

We acknowledge the support of FORCLIMSOC Nucleu Programme (Contract No. 12N/2023) Project ID PN23090203 entitled “New Scientific Contributions for Sustainable Management of Watersheds, Degraded Lands, Forest Shelterbelts and Other Agroforestry Systems in the Context of Climate Change”, financed by the Ministry of Education and Research.

REFERENCES

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. *Fitting Linear Mixed-Effects Models Using lme4.* Journal of Statistical Software, 67. https://doi.org/10.18637/jss.v067.i01

Boinot, S., Fried, G., Storkey, J., Metcalfe, H., Barkaoui, K., Lauri, P., Meziere, D., 2019. *Alley cropping agroforestry systems: Reservoirs for weed or refugia for plant diversity?* Agriculture, Ecosystems & Environment, 284, 106584. 10.1016/j.agee.2019.106584

Burgess, P.J., and Rosati, A., 2018. *Advances in European agroforestry: results from the AGFORWARD project.* Agroforest Systems, 92: 801-810. https://doi.org/10.1007/s10457-018-0261-3

Chalupecká, H., Jačka, L., Kuželková, M., Kovář, M., Rous, J., Abbasizadeh, H., Komáreck, J., Preininger, D., Lojka, B., 2026. *The early-stage effect of alley cropping system on the soil moisture and temperature of drought-prone silt-loam soil in European temperate transitional climate.* Agroforestry Systems, 100: 78. https://doi.org/10.1007/s10457-026-01436-4

Donat, M., Geistert, J., Grahmann, K., Bellingrath-Kimura, S.D., 2023. *Orientation of tree rows in alley cropping systems matters - The “ShadOT” modelling tool for tree growth and shading effects.* MethodsX, 11: 102282. https://doi.org/10.1016/j.mex.2023.102282

Greene, H., 2025. *Can you grow trees and grain together?* https://www.propagateag.com/blog/alley-cropping (accessed 2 July 2026).

Honfy, V., Pödör, Z., Keserű, Z., Rásó, J., Ábri, T., Borovics, A., 2023. *The Effect of Tree Spacing on Yields of Alley Cropping Systems - A Case Study from Hungary*. Plants, 12, 595. https://doi.org/10.3390/plants12030595

Ivezić, V., Yu, Y., Werf, W.V.D., 2021. *Crop Yields in European Agroforestry Systems: A Meta-Analysis*. Frontiers in Sustainable Food Systems, 5, 606631. https://doi.org/10.3389/fsufs.2021.606631

Jose, S., 2009. *Agroforestry for Ecosystem Services and Environmental Benefits: An Overview*. Agroforestry Systems, 76: 1-10. http://dx.doi.org/10.1007/s10457-009-9229-7

Koch, O., Moore, J., Hörl, J., Cormann, M., Gayler, S., Lewandowski, I., Marhan, S., Munz, S., Pflugfelder, M., Piepho, H.-P., Schneider, J., Von Cossel, M., Weinand, T., Winkler, B., Schweiger, A.H., 2025. *Sheltered by trees: long-term yield dynamics in temperate alley cropping agroforestry with changing water availability*. Agronomy for Sustainable Development, 45, 27. https://doi.org/10.1007/s13593-025-01022-5

Maitra, S., Sairam, M., Sagar, L., Ray, S., Santosh, D.T., Gaikwad, D.J., Atapattu, A., Gitari, H., 2025. *Alley Cropping: A sustainable agroforestry system for enhancing productivity, soil health and biodiversity.* In: Tariq, A. (eds.), Plant Biotechnology and Sustainable Agriculture: Bridging the Gap for Global Food Security. CABI: 235-248. https://doi.org/10.1079/9781800627659.0016

Majaura, M., Böhm, C., Freese, D., 2024. *The influence of trees on crop yields in temperate zone alley cropping Systems: A review.* Sustainability, 16: 3301. https://doi.org/10.3390/su16083301

Mihăilă, E., Tudora, A., Bîtcă, M., Popovici, L., 2021. *Alley cropping versus taungya system, two distinct types of agroforestry systems.* Revista de Silvicultură și Cinegetică, 49: 72-80. (In Romanian with abstract in English)

Mușat, M., Ciceoi, R., Dolocan, C., Argatu, G., Cioroianu, I., 2021. *Increasing the productive potential of agroecosystems affected by climate change using shelterbelts, in the southeastern part Romania*. Romanian Agricultural Research, 38: 505-515. https://doi.org/10.59665/rar3853

Oelbermann, M., Voroney, R.P., Gordon, A., 2004. *Carbon sequestration in tropical and temperate agroforestry systems: a review with examples from Costa Rica and southern Canada.* Agriculture, Ecosystems & Environment, 104(3): 359-377. https://doi.org/10.1016/j.agee.2004.04.001

Quinkenstein, A., Wöllecke, J., Böhm, C., Grünewald, H., Freese, D., Schneider, B.U., Hüttl, R.F., 2009. *Ecological benefits of the alley cropping agroforestry system in sensitive regions of Europe.* Environmental Science & Policy, 12: 1112-1121. https://doi.org/10.1016/j.envsci.2009.08.008

Reuse, C., and Langhof, M., 2025. *The impact of tree height and distance on crop yields in a temperate short rotation alley cropping agroforestry system: a multi-year study.* Agroforest Systems, 99: 140. https://doi.org/10.1007/s10457-025-01237-1

Rivera-Pedroza, L.F., Escobar, F., Philpott, S.M., Armbrecht, I., 2019. *The role of natural vegetation strips in sugarcane monocultures: Ant and bird functional diversity responses.* Agriculture, Ecosystems & Environment, 284: 106603. https://doi.org/10.1016/j.agee.2019.106603

Seserman, D.-M., Freese, D., Swieter, A., Langhof, M., Veste, M., 2019. *Trade-Off between Energy Wood and Grain Production in Temperate Alley-Cropping Systems: An Empirical and Simulation-Based Derivation of Land Equivalent Ratio.* Agriculture, 9, 147. https://doi.org/10.3390/agriculture9070147

Tudora, A., Bîtcă, M., Mihăilă, E., 2022. *Evolution of the agroforestry system of the alley cropping type in the first years after plantation.* Revista de Silvicultură și Cinegetică, 51: 74-81. (In Romanian with abstract in English)

Van Lerberghe, P., 2017. *Alley cropping systems: key objectives.* https://www.agforward.eu/documents/leaflets/Best Practices/01_Alley_cropping_system_key_objectives.pdf (accessed 2 July 2026).

Veldkamp, E., Schmidt, M., Markwitz, C., Beule, L., Beuschel, R., Biertümpfel, A., Bischel, X., Duan, X., Gerjets, R., Göbel, L., Graß, R., Guerra, V., Heinlein, F., Komainda, M., Langhof, M., Luo, J., Potthoff, M., Van Ramshorst, J.G.V., Rudolf, C., Seserman, D.-M., Shao, G., Siebicke, L., Svoboda, N., Swieter, A., Carminati, A., Freese, D., Graf, T., Greef, J.M., Isselstein, J., Jansen, M., Karlovsky, P., Knohl, A., Lamersdorf, N., Priesack, E., Wachendorf, C., Wachendorf, M., Corre, M.D., 2023. *Multifunctionality of temperate alley-cropping agroforestry outperforms open cropland and grassland.* Communications Earth & Environment, 4: 1-10. https://doi.org/10.1038/s43247-023-00680-1

Wolz, K.J., and DeLucia, E.H., 2018. *Alley cropping: Global patterns of species composition and function.* Agriculture, Ecosystems & Environment, 252: 61-68. https://doi.org/10.1016/j.agee.2017.10.005

Xu, H., Bi, H., Gao, L., Yun, L., 2019. *Alley cropping increases land use efficiency and economic profitability across the combination cultivation period*. Agronomy, 9(1), 34. https://doi.org/10.3390/agronomy9010034