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Exploring the Branch Wood Supply Potential of an Agroforestry System with Strategically Designed Harvesting Interventions Based on Terrestrial LiDAR Data

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Abstract: Agroforestry systems hold potential for wood and tree biomass production without the need of felling trees. Branch wood harvesting provides access to considerable amounts of lignocellulosic biomass while leaving the tree standing. Aiming at alternatives for wood provision, we assessed the actual woody structure of a silvopastoral system in the African Savannah ecoregion, utilising terrestrial LiDAR technology and quantitative structure models to simulate branch removals and estimate harvesting yields. In addition, the stand structure and harvested wood were examined for the provision of four types of assortments meeting local needs, and operational metrics for each treatment were derived. The stand had large variability in woody structures. Branch harvesting interventions removed up to 18.2% of total stand volume, yielded 5.9 m^3 ha^{-1} of branch wood, and delivered 2.54 m^3 ha^{-1} of pole wood quality, retaining on average more than 75% of the original tree structures. Among the most intense simulations, a mean of 54.7 litres (L) of branch wood was provided per tree, or approximately 34.2 kg of fresh biomass. The choice of an ideal harvesting treatment is subject to practitioners' interests, while the discussion on aspects of the operation, and stand and tree conditions after treatment, together with outputs, assist decision making. The partitioning of tree structures and branch removal simulations are tools to support the design of tending operations aiming for wood and tree biomass harvesting in agroforestry systems while retaining different functional roles of trees in situ.

Keywords: Namibia; savannah; silvopasture; QSM; pruning; biomass; TLS

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1. Introduction

Agroforestry systems (AFS) include a wide range of woody perennials associated with agricultural crops and/or livestock to produce goods and services, and are postulated as an appropriate response to climate change [1,2]. The productive function of woody perennials is frequently associated with the provision of timber and other woody biomass, though trees assume more complex protective and regulatory functions in AFS [3,4]: wind protection, shading of food crops [5,6], soil erosion control, and pollution control, among others. The provision of tree-derived raw materials in AFS is a direct and often indirect source of income for agroforestry practitioners. As woody resources are scarce, AFS can reduce pressure on woody resources of natural forests by supplying biomass without the need to fell trees, thereby completely extinguishing the trees' functions as mentioned above.

AFS often support farmers' subsistence and compete with industrial agriculture (e.g., monocultural systems); thus, the derived collection of goods and services must balance economic interests, transforming it into a competitive land-use system. In addition, since AFS have a higher level of complexity and are more labour-demanding than monocultures, such systems often have higher management costs, which are offset by the system's benefits and services. Southern African savannahs are heterogeneous ecosystems where AFS are widely practised [7], where trees assume many roles (e.g., as fertiliser trees), and where goods and services provided by woody perennials help achieve family securities (e.g., source of food, medicine, fodder, shelter, energy, income) and environmental security. Hence, the planning and management of AFS can cope with these challenges, while technical knowledge assists decision making in AFS, e.g., for the selection of efficient wood and biomass harvesting systems and tending operations.

Biomass removals are interventions providing woody resources derived from trees as the output of a harvesting operation (e.g., branch harvesting) or as a tending operation (e.g., pruning). In agroecosystems, key factors determining the amount of biomass removal are the actual stand density and the development stage, although this is subject to many factors [8]: crop characteristics (i), such as species, cultivar, or provenances, rootstock, and age; management and tending practices (ii), such as irrigation regime, fertilisation, planting design, training system; and edaphoclimatic conditions (iii), e.g., soil type and rainfall pattern. Further, as branch harvesting alters tree and stand conditions, the state of the agroecosystem has to be considered when designing such operations [9,10].

The utilisation of residual biomass originating from pruning interventions has received more attention in agriculture than in forestry and agroforestry [11,12]. Pari et al. [8] reported European orchards yielding 13 million tonnes of dry pruning biomass annually. Such residues are often seen as a resource for bioenergy [13]. Common agricultural residue stocks are branches, leaves, kernels, stalks, and straw [12]. Biomass residues are frequently estimated through average agricultural data (e.g., yield tables) calibrated for the number of trees and cultivated land area [12]. Likewise, the need to quantify and classify residues from agroecosystems, assuming them as yield rather than waste, led to the development of predictive tools, including cultivation variables and dendrometric techniques for different tree species [14]. For example, fruit trees are perennials that remain productive for decades [12]; thus, it is essential to consider the quantity of waste biomass available and the cyclic production rates (e.g., annual or biannual). The fresh and dry pruning residues are reported as residue to surface ratio (RSR), in tonnes per hectare [8], or as oven-dry pruning biomass production ratio, in tonnes of dry matter per hectare [15].

Recently, non-invasive three-dimensional digitisation with terrestrial LiDAR (Light Detection and Ranging; in the form of TLS; Terrestrial Laser Scanning) enabled the quantification of many landscape components (e.g., trees) with the highest level of detail and precision among competing technologies [16]. TLS is used for assessing the structural composition and monitoring the temporal dynamics of trees within forests and AFS [17–19], thus, aiding estimations of woody volume and biomass availability that could be extended to the evaluation of harvest yields. Muumbe et al. [20] emphasised the potential of terrestrial LiDAR for an accurate assessment of forest resources and extraction of tree attributes for the Savannah vegetation. Tree parameters can be extracted from project point clouds produced by sequenced scanning positions, ensuring a full 3D representation. Individual tree point clouds are used for fitting quantitative structure models (QSMs), which rebuild tree form with cylinders. A stable and well-documented approach for calculating QSMs is *TreeQSM* [21,22]. The QSMs contain accurate volumetric, topological, and geometrical tree properties that can be manipulated as database queries to select the woody compartments' specific characteristics. Lately, the use of QSMs has opened up new possibilities for modelling the tree shading effects, the influence of pruning concerning insolation reduction, and many other ecological applications [23–25]. Using the volume derived from TLS, the biomass amount can be derived using the wood density from specific species [26].

In this study, we provide a comprehensive vision of AFS as reduced-felling systems by presenting an integrated methodology for evaluating woody resources theoretically available in one AFS. After retrieving structural information on the stand conditions, branch harvesting treatments were simulated and examined for the availability of wood assortments demanded by local stakeholders and regional markets. To our knowledge, this is the first instance where TLS data have been used to estimate branch harvesting yields from standing trees, while the identification of assortments has been recently explored [27]. We hypothesise that such a combined approach could create targeted wood and biomass interventions to facilitate their evaluation and implementation while targeting desired tree products and maintaining desired auxiliary functions trees play in certain AFS.

In the context of this work, we use the ecological term "biomass" in reference to the mass of woody plant material within the given system. We recognise that the term biomass is also synonymous with plant-based material used as a fuel stock. This of course is also of high relevance to AFS, the harvesting of tree parts, and for the support of livelihoods, and is referred to as residual wood or fuel wood within our context.

2. Materials and Methods

2.1. Site Description

The research site is located near Rundu (Namibia; 18°12′33″ S 19°38′05″ E, 1180 m a.s.l.), inside the Kavango region, and is part of the Hamoye Forest Reserve, owned by the national government of Namibia (Figure 1). The regional mean annual air temperature is 22.6 °C (range 1.8–43.9 °C), while the mean annual precipitation sum is 527 mm (range 348–816 mm), markedly summer rainfall [28,29]. Soils are generally classified as Arenosols, primarily dominated by a deep soil layer with rapid permeability, low water-holding capacity, and low nutrient content [29–31].

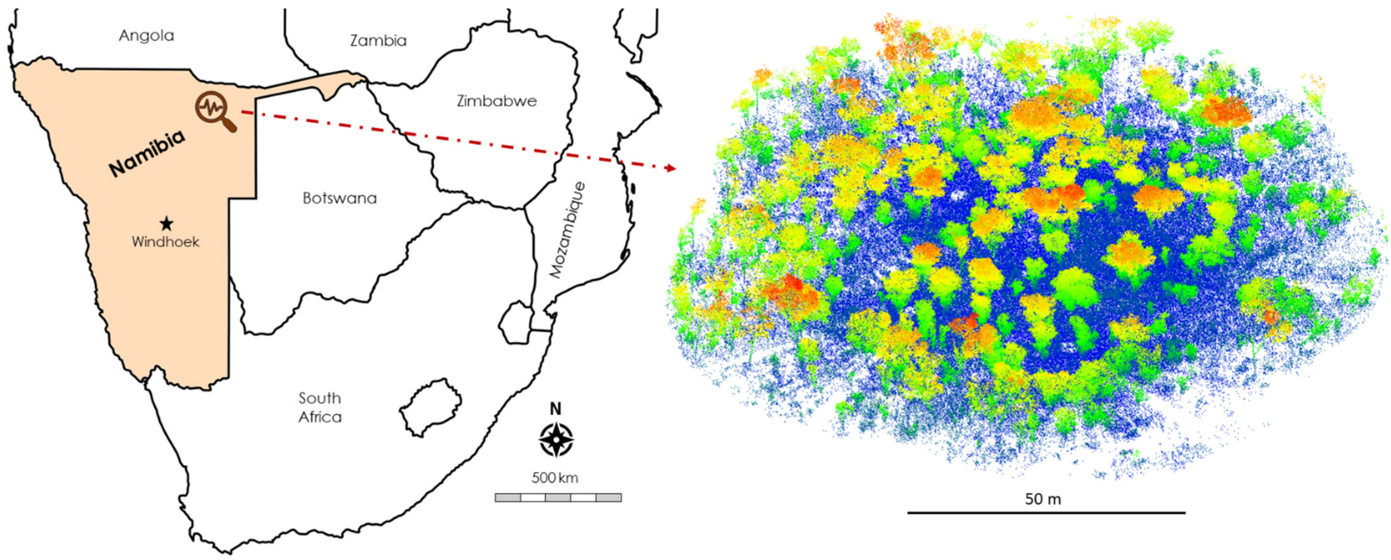

Figure 1. Location of the study site (**left**) and overview of the project's point cloud (**right**). Colour palette indicates vertical stratification: blue (ground-level) to red (treetops).

Domestic livestock regularly graze the woodland area. Wildfires, mostly non-intentional fires, are a prominent feature not only of this experimental site in particular but are broadly acknowledged as being an integral part of the southern African tropical forests and savanna woodlands, occurring with a return interval of one to approximately five years [29,32,33]. The tree stand was thinned to 40% of its basal area in 2016, resulting in a tree density of ca. 145 trees ha^{-1}, composed of *Burkea Africana* Hook (50%; ±72 trees ha^{-1}), *Pterocarpus angolensis* DC. (33%; ±48 trees ha^{-1}), *Guibourtia coleosperma* (Benth.) J. Léonard (11%; ±16 trees ha^{-1}), and other tree species (6%; 8 trees ha^{-1}). In our study site, trees are spatially scattered, with few clusters of moderately touching tree crowns. Other tending operations have not been applied to the individual trees.

Essential provisioning services of the woodlands in the region are the supply of fuelwood, household construction materials (primarily poles), sawn timber (mainly *P. angolensis*), and wood for utensils and carving [34,35]. Other ecosystem services include livestock grazing, provision of shade and shelter for livestock, tree fodder, and limited quantities of edible nuts and fruits, such as Manketti nuts (*Schinziophyton rautanenii* (Schinz) Radcl. SM) and monkey-oranges (*Strychnos cocculoides* Baker).

2.2. Acquired 3D Data and Processing

A sampling campaign was conducted in May 2018 (autumn, dry season) with a RIEGL VZ 400 (*RIEGL* Laser Measurement Systems GmbH; Horn, Austria) terrestrial laser scanner set to the high-speed mode (300 kHz laser repetition rate, 122,000 measurements per second). In an irregular design, five scanning positions were placed approximately 25 m and 90 degrees apart from the central position. Trees had lower foliage densities due to leaf shedding after summer, while few species are deciduous (e.g., *P. angolensis*).

The point clouds of each scanning position were co-registered with RiSCAN PRO v2.8 (*RIEGL* Laser Measurement Systems GmbH; Horn, Austria) following the standard software protocol, filtering scanning positions by a range of 50 m, and exported in LAS format. From the project point cloud, in an area equivalent to 0.455 ha (65 × 70 m), individual tree point clouds were snipped out and subsequently filtered by intensity information to separate foliage from woody structures (see Figure S1). For the homogenisation of the point cloud, cubical downsampling was applied with a side length of 2 mm.

2.3. Tree Structures

We retrieved the 3D tree structures from the processed individual tree point clouds employing QSMs using the MATLAB implementation of *TreeQSM* version 2.4 (https://github.com/InverseTampere/TreeQSM, accessed on 19 April 2022) [21,22]. In *TreeQSM*, trees are represented by a hierarchical collection of cylinders fitted to local details of their digital twins (the point clouds). Following the recommendations by Raumonen [36], we optimised the QSM fitting for each tree by testing 36 combinations of possible key input parameters and produced 25 models for each parameter combination, from which the precision of the QSMs could be estimated.

The tested input parameters were (in metres): cover patch diameters (d) in the first segmentation, 0.04, 0.08, 0.12; minimum d in the second segmentation, 0.010, 0.015, 0.020, 0.025; and maximum d in the second segmentation, 0.030, 0.045, 0.060. The minimum number of points in the first segmentation was set to five. As a suitable metric for model selection, we opted for the 'standard deviation of trunk plus branch volume', as it gives equal weight to trunk and branches (e.g., in many situations, branch-cylinders are larger in number than stem-cylinders). The final QSMs were reconstructed with their best-input parameters.

The stand-level QSM-derived tree parameters are presented in Table 1. There was a large variation in tree structure revealed by the number of branches, and total tree and branch volume. Tree height had a lower range variation and the highest precision of the assessed parameters, while the uncertainty of total tree volume stayed below 10%. Selected trees are explained in Section 2.4. The QSM-derived tree attributes can be found in Table S1 and the optimised input parameters in Table S2.

Table 1. Summary of QSM-derived tree parameters and coefficients of variation for the research plot.

Tree Attributes	Unit	Stand (n = 66)		Selected Trees (n = 49)	
		μ ± σ	CV%	μ ± σ	CV%
Diameter at breast height	cm	14.6 ± 8.3	13.6 ± 11.9	17.7 ± 7.0	7.6 ± 5.7
Tree height	m	8.3 ± 2.8	3.5 ± 5.7	9.2 ± 2.3	3.4 ± 6.4
Branch volume	L	113.4 ± 122.8	11.9 ± 5.9	138.9 ± 128.2	10.2 ± 5.4
Total volume	L	223.1 ± 224.8	9.1 ± 6.2	281.1 ± 230.4	7.7 ± 6.0
Number of branches	-	75 ± 80	11.2 ± 7.5	89 ± 85	10.5 ± 8.4
Max branch order	-	4 ± 2	14.9 ± 4.6	4 ± 2	13.4 ± 3.8
Branch length	m	70.4 ± 65.8	9.4 ± 6.6	81.4 ± 66.4	8.7 ± 7.1
Mean crown diameter	m	2.9 ± 2.0	6.7 ± 4.0	3.3 ± 1.9	6.0 ± 3.9
Crown base height	m	2.1 ± 1.2	19.1 ± 21.2	2.3 ± 1.3	17.3 ± 20.8
Total woody surface area	m^2	11.19 ± 9.34	6.9 ± 4.6	13.36 ± 9.23	6.1 ± 3.9

μ: mean; σ: standard deviation; CV%: coefficient of variation in percentage.

2.4. Woody Compartments and Branch Harvesting

Woody biomass can be categorised into stem and branch components, and thus, can be harvested in part (branches or tree parts) or as a whole tree (stem and all branch ramifications). Woody biomass including the branch biomass compartment is an important source of tree fodder, fuelwood, medicinal wood, or other by-products resultant of the operations improving the growing conditions for crops (e.g., management of shading effects, pruning for fruit production, or as a method of increasing wood quality, crop competition, etc.). We combined the geometric features of the modelled tree structures, such as the relative position (XYZ coordinates), the size (e.g., diameter, length, volume), and topological information (e.g., branch orders), and assessed cylinders meeting specific criteria. The woody compartments are defined in Table 2.

Table 2. Branch selection properties for branch harvesting simulations.

Simulation by	Selection Criteria	Thresholds	Treatments
Height	All first-order branches with a branch base height below the threshold are removed with their ramifications	H ≤ 2 m H ≤ 3 m	*H2* *H3*
Diameter	All first-order branches with a branch collar diameter above the threshold are removed with their ramifications	BCD ≥ 2 cm BCD ≥ 7 cm	*Di2* *Di7*
Branch order	All branches of second-order and ramifications attached to a first-order branch with a collar diameter meeting the threshold are removed	BO ≥ 2 and BCD ≥ 4 cm	*BrO*

BCD: branch collar diameter; BO: branch order; H: tree height.

For the assessment of production potential, we used the above defined woody compartments to simulate branch harvesting at the stand level by manipulating the initial tree structures (the QSMs), retrieving harvesting yields and generating metrics related to the branch removal operation in a computer environment. We designed five treatments aiming to fulfil the scope of wood supply while seeking to maintain other tree functionalities: two height-based branch harvesting treatments (*H2* and *H3*), where all first-order branches and ramifications with a branch base height below the threshold are removed; two selective branch removals, based on first-order branch collar diameter (*Di2* and *Di7*), where all first-order branches and ramifications with a branch collar diameter above the threshold are removed; and removal of higher-order branches (*BrO*), with defined diameter thresholds for first-order branches. In the case of *BrO*, all first-order branches with a diameter ≥4 cm were pruned by cutting their second-order branches. All approaches were implemented as bottom-up interventions, progressing to 3 m in tree height (except *H2*, limited to 2 m), and designed as non-mechanised techniques (i.e., possible to implement by using simple tools only), meeting the local conditions of the studied area.

The five branch harvesting treatments (Table 2) were applied to the QSM of all trees with a diameter at breast height (DBH, measured at 1.3 m from the ground) equal to or greater than 7.0 cm (n = 49, henceforth 'selected trees'), totalling 245 simulated tree structures. The assessed woody compartments are illustrated in Figure 2. Furthermore, we derived metrics from the simulated branch harvesting treatments to evaluate the operations beforehand concerning the stand and the trees: (i) the number of trees with branches removed; (ii) the number of first-order branches altered; (iii) the number of cuts (mean per tree and total); (iv) the cut surface per number of cuts; (v) the total cut surface; (vi) the branch wood volume per cut; (vii) the average retained tree structure, and; (viii) the harvested branch wood volume per tree.

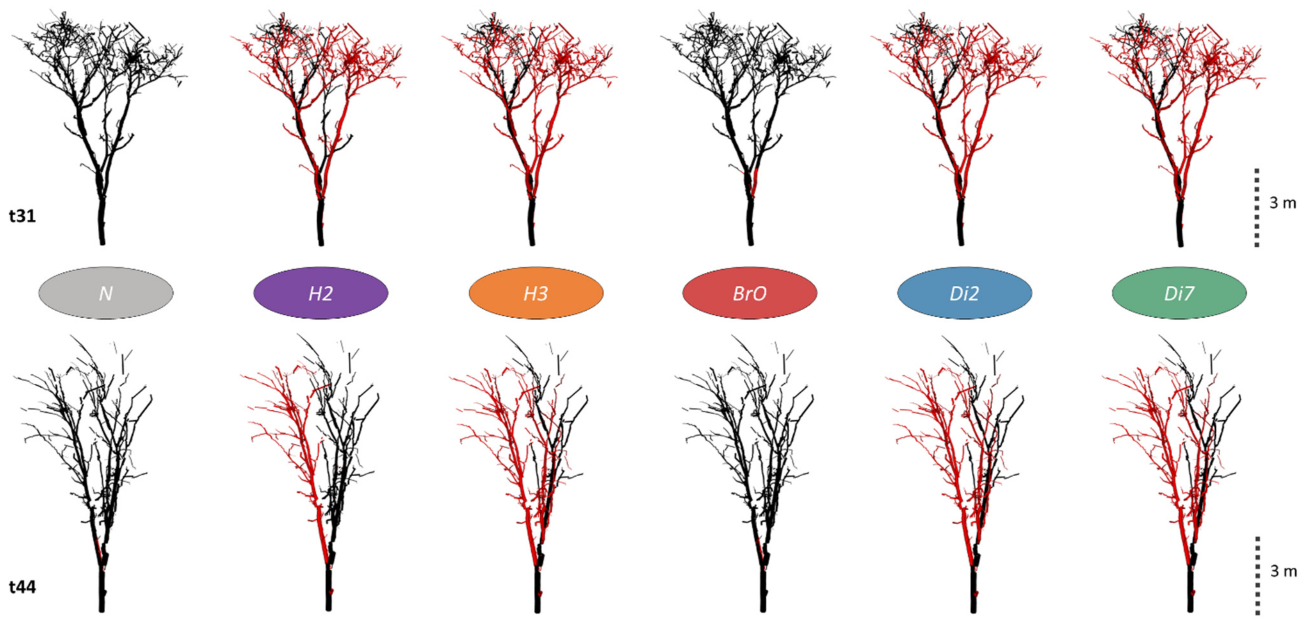

Figure 2. Tree structures (QSMs) for trees *t31* and *t44* with queried branches in red (wood to be removed).

2.5. Wood Assortments

Following the typical use and wood demand for household consumption and the local market's needs, we categorised the tree structures and the assessed woody compartments into four main assortments. The assortments were defined as uninterrupted wood sections respecting the continuity of the tree parts (stem and branches): (i) pole wood, pieces with length $\geq$2 m and cross-sectional diameter $\geq$7 cm; (ii) carving wood, with a length of $\leq$2 m and a diameter of $\geq$7 cm; (iii) fencing poles, with a length of $\geq$1.2 m, and a diameter of $\geq$2 cm and $\leq$7 cm, and; (iv) residual wood (e.g., fuelwood), length $\leq$1.2 m and/or a diameter of $\leq$2 cm. To conclude, the assortments' yields were evaluated at stand level.

2.6. Algorithms and Analysis

Descriptive statistics were computed to synthesise the main features of the potential branch wood yields, assortments, and pruning operations. The applied algorithms were written as independent functions in the open-source language R version 3.5.3 (R Core Team 2019; Vienna, Austria) to retrieve the relevant output from the QSMs matching the specific database queries. The functions have particular input parameters and the following outputs: the tree structure following treatment, the branch residuals, a summary and visualisation of the performed intervention. Similarly, the metrics of the applied harvesting simulations and the wood assortments were retrieved by manipulating the data and coding.

3. Results

3.1. Stand and Tree Volume

The stand had a density of 145 trees ha^{-1}, with a basal area of 3.19 m^2 ha^{-1}, and a total woody volume of 32.37 m^3 ha^{-1}, totalling 15.91 m^3 ha^{-1} of stem volume and 16.46 m^3 ha^{-1} of branch volume. Selected trees (the ones subjected to branch harvesting treatments; DBH $\geq$ 7 cm), had a density of 108 trees ha^{-1}, with a basal area of 3.10 m^2 ha^{-1}, a total woody volume of 30.3 m^3 ha^{-1} (94% of the total standing volume), and trunk and branch volumes of 15.31 m^3 ha^{-1} and 14.99 m^3 ha^{-1}, respectively. Moreover, the selected trees had a mean DBH of 17.7 cm (range 7.2–32.2 cm), a mean tree height of 9.2 m (range 4.1–13.7 m), and a mean tree volume of 281.4 $\pm$ 230.1 L, divided between 142.2 L trunk volume (50.5% of total mean tree volume), and 139.2 L branch volume (49.5% of total volume). The average accumulated length of all branches for a single tree was 81.4 $\pm$ 66.4 m. Tree branches were ramified in four branch orders (median), and trees had an average crown diameter of 3.3 $\pm$ 1.9 m and a crown area of 18.65 $\pm$ 17.99 m^2. The average crown base height of all trees was 2.3 $\pm$ 1.3 m.

3.2. Branch Wood Yields and Assortments

The estimated branch wood yields are displayed in Figure 3. None of the harvesting simulations were applied to all trees in the stand (maximum 97 trees ha^{-1} in *H3*), and the wood yields ranged from 0.2 to 5.9 m^3 ha^{-1}, in *BrO* and *H3* (Figure 4). In comparison, *Di2* had a similar yield to *H3*, and *Di7* emphasised the abundance of wood retained in the branches of greater dimensions. Likewise, the difference in yields from *H2* and *H3* is an effect of the height threshold. Concerning the total stand volume, extraction of woody materials corresponded to up to 18.2% (*H3* and *Di2*), or 36% of the standing branch volume. As a minor effect, *BrO* removed less than 1% of the standing volume or 1.1% of the branch volume.

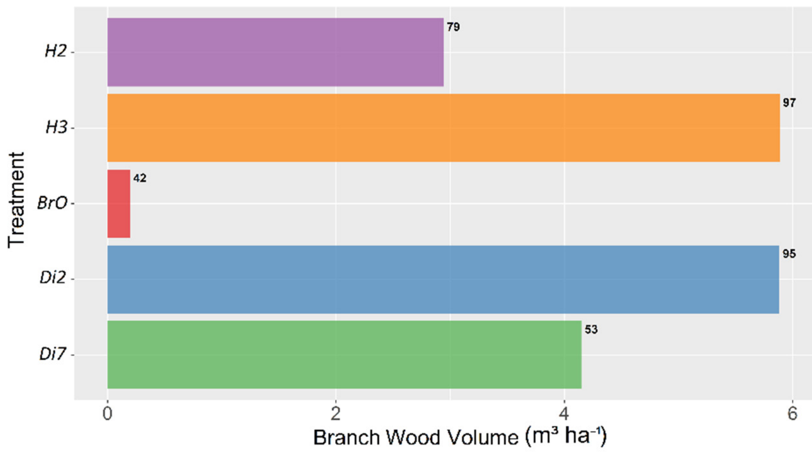

Figure 3. Potential branch wood yields for simulated harvesting treatments with the number of trees altered by branch removals at the right end of the bars.

According to the applied harvesting simulations, the wood assortments harvested from the selected trees were: 20.67 m^3 of pole wood, 1.42 m^3 of carving wood, 5.44 m^3 of fence wood, and 2.77 m^3 of residual wood (Table S3). Stem wood could be produced by harvesting whole trees, but 99 trees ha^{-1} supplied pole wood quality from branches, while only 64 trees ha^{-1} had at least 0.1 m^3, and 35 trees ha^{-1} could provide more than 0.2 m^3 of this assortment (Supplementary File S2).

Harvesting simulations *H3* and *Di2* delivered 2.54 m^3 ha^{-1} of pole wood quality, while *Di7* and *H2* yielded 2.33 m^3 ha^{-1} and 1.15 m^3 ha^{-1}, respectively (Figure 4). The production of any of the assortments was maximised in *H3* and *Di2*, while *BrO* delivered less than 1 m^3 ha^{-1} of wood. Treatments *H3* and *Di2* produced 1.8 m^3 ha^{-1} of fencing wood, 0.46 m^3 ha^{-1} of carving wood, and ~1.1 m^3 ha^{-1} of residual wood. Branch wood yields in linear metres are available in Table S3.

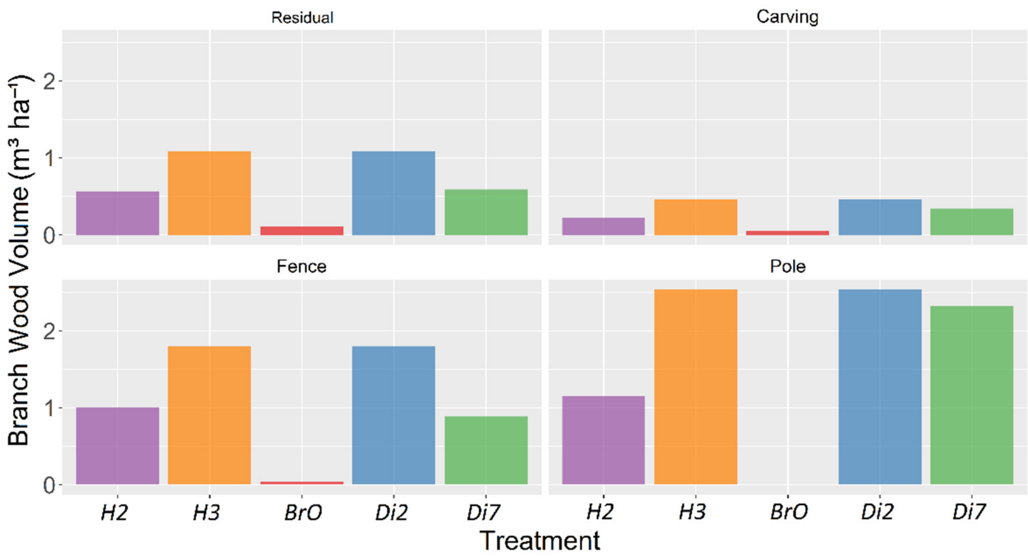

Figure 4. Stand-level wood assortments volume as yields of harvesting simulations.

3.3. Branch Removal Operations

Simulated branch removals altered up to 67% of the trees in the stand (*H3*), whereas treatments *Di7* and *BrO* modified fewer trees (Table 3). Similarly, the relative number of altered first-order branches (OB) in ascending order was: *Di7* < *BrO* < *H2* < *Di2* < *H3*.

Table 3. Operation summary of harvesting simulations.

Measure	Unit	*H2*	*H3*	*BrO*	*Di2*	*Di7*
Tree alterations	%	54.5	66.7	28.8	65.2	36.4
First OB alterations	%	16.8	27.6	7.0	25.8	6.2
Number of cuts	cuts tree^{-1}	2.8	3.8	5.6	3.6	1.5
	cuts ha^{-1}	222	365	235	341	81
Mean cut area	cm^2 cut^{-1}	33.1	36.7	13.1	39.2	105.1
Total cut area	m^2 ha^{-1}	7.35	13.41	3.08	13.36	8.54
Wood vol. per cut	L cut^{-1}	18.3 ± 49.8	24.5 ± 48.5	1.1 ± 1.3	26.5 ± 49.7	57.2 ± 76.6

The lowest number of cuts was found in *Di7* (81 cuts ha^{-1}), as it focused on branches of greater dimensions, with an average of 1.5 cuts per tree and an average surface cut of 105.1 cm^2 per cut, indicating the greater size of the pruned materials.

With the highest pruning yields, *H3* altered 66.7% of the standing trees, producing a total of 365 cuts ha^{-1} and a mean of 3.8 cuts per tree, with a total surface cut area of 13.41 m^2 ha^{-1} and 36.7 cm^2 per cut (mean diameter of ≈6.8 cm), yielding a branch wood volume of 24.5 ± 48.5 L per cut. Results of *Di2* were analogous to *H3*.

The minimum total cut area of 3.08 m^2 ha^{-1} was found in *BrO*, yielding only 1.1 L per cut due to the small size of the cut material (13.1 cm^2 per cut), however, it presented a high number of cuts in comparison with other treatment variants.

3.4. Retained Tree Structures and Removed Materials

The applied treatments removed branches to a height of 3 m (except treatment *H2*), and the relative retained tree volume is presented in Figure 5. All pruning simulations retained more than 75% of individual tree structures on average. Moreover, medians were greater than the means, which indicated a superior structure kept in most of the individuals.

The average retained tree structure in ascending order was (from 76.5% to 98.8%): *H3* < *Di2* < *H2* < *Di7* < *BrO*. *BrO* displayed the highest retained volume, with a value of 98.8%. Over 90% of the original tree structures were retained with *Di7*, while *Di2* and *H3* had mean retained volumes of around 75% showing coefficients of variation above 30%.

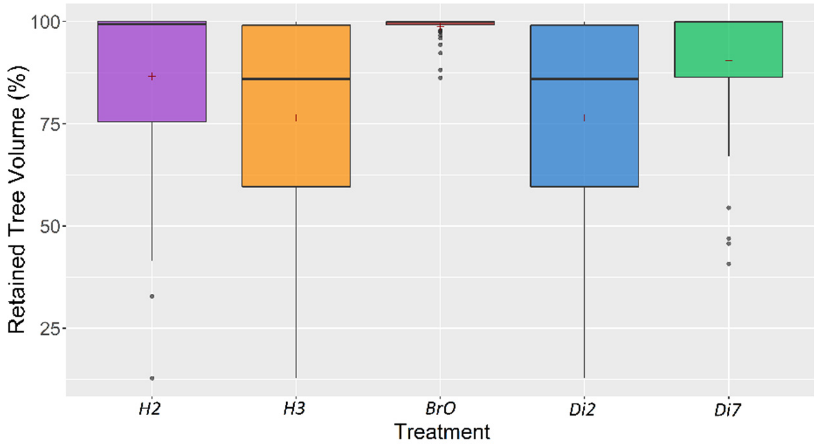

Figure 5. Boxplots of the relative retained tree volume for the harvesting simulations with crosses representing the treatment's mean.

At tree level, mean branch wood yields ranged from 1.8 to 54.7 L tree^{-1} for *BrO* and *H3*, respectively (Figure S3, Supplementary File S2). A small number of trees yielded up to ≈320 L of woody materials, reflecting the structural variability of the sample stand.

4. Discussion

Trees in AFS are managed to maintain specific functions and provide certain goods and services, including the supply of wood for different purposes, which can be qualified within wood assortments. Since whole-tree harvesting is less frequently an option in many AFS, branch wood removal could be beneficial for releasing wood and biomass while keeping functional trees to the production targets, mediating interactions between agroforestry components, and generating income. The current integrated approach can facilitate the challenge of wood and biomass yield assessment. Once the woody compartments were identified, quantified, and categorised, we recognised a potential for enhanced management in AFS with strategically designed harvesting simulations.

The great structural variation found on a tree-by-tree basis reflects the structural variation of the reference stand. Luck et al. [37] also found considerable variability in tree form in Australian tropical savannahs. Regarding the assessment, often TLS-derived and harvested aboveground biomass agree to within 10% error at the individual tree level [26].

The removal of second-order branches (e.g., *BrO*) had the lowest mean surface cut area of 13.1 cm^2 per cut but the highest relative number of cuts (5.6 per tree). This resulted in a removal of 1.1 L of branch wood per cut for 42 trees per hectare. The lowest wood yield of 0.19 m^3 ha^{-1} (<1% of total stand volume) makes the *BrO* treatment unviable, though it released 123 m of cooking wood and 21 m of fencing material (Figure S2). This treatment could become more attractive in well-established trees with larger dimensions. Removals at the branch-order level can be prioritised for trees with high economic interest (e.g., medicinal wood).

Due to the high branchiness found in lower parts of many trees, *H3* yielded 5.89 m^3 ha^{-1} even if limited to 3 m in tree height. This treatment would release nearby crops from the competition and create space for livestock with a high chance of retaining beneficial tree shading effects. Moreover, *H2* and *H3* can reduce the ladder fuel that could escalate ground fires to the canopy level. Simulations extended to upper canopy layers could be used, though that would modify the operation's mechanisation level and require expertise. In all simulations (except *BrO)*, the estimated number of cuts in each harvesting intervention is under-representative for branches of larger dimensions, as they are likely to require one or more auxiliary cuts before the final cut (removing the whole branch), to avoid damages to the tree (i.e., relief cuts).

In AFS, wood and biomass removals are designed within the framework of a system's scale, and tree, crop, and livestock interactions. Agricultural crops, in many cases, drive the timing of tree operations (e.g., harvesting or pruning), as fields have to be ready for the seasonality of cultivations. Likewise, the timing for biomass removals can be economically driven (e.g., lack of income or price advantage) or due to scarcity of fuelwood for cooking or processing goods (e.g., tobacco). One key aspect is the available space for crops and/or animals, as lower branches are likely to impede crop production or irritate livestock. The removal of lower branches reduces crown competition (e.g., *H2* and *H3*), and also functions as a firewise pruning treatment, as it dissociates tree crowns from low-intensity ground fires and reduces ladder fuels. Tree species respond differently to biomass removals (e.g., frequency, intensity) due to their specific traits, health state, environmental conditions (or growing conditions), and risk of pests. For this reason, it is crucial to associate the specific knowledge on ecology and growth reactions of specific tree species.

Other common vegetation structures that could release considerable amounts of biomass are windbreaks, hedges, live fences [38], green belts, fruit orchards, vineyards, olive groves and widely spaced tree plantations, or parklands. As an alternative to the "post-treatment" quantification of biomass [15,39], our approach could also be applied in scenarios where trees are pruned for a productive or qualitative goal, such as in fruit orchards, where pruning intensity can alter fruit yield and quality [40].

In order to qualify the presented treatment variables, Table 4 gives and overview of each harvesting simulation, and its effect on stand and tree health, the derived product, and on the labour implications of its execution. The removal of tree branches creates open wounds which act as an entry portal for woody decay organisms. A larger wound is slower to occlude, and thus, increases the risk of wood decay. Small cut faces facilitate a swift occlusion of wounds. This is beneficial to limit the egress of decay organisms into woody tissues [41], thus, limiting detrimental effects on tree health. Here, we suggest that the more invasive treatments have a greater detrimental impact on stand and tree health. Differences in treatment also have implications on the quantity and quality of products derived from the stand. Those treatments that are more invasive will produce greater quantities but not necessarily increase quality (where it is required). However, quality aspects may be impacted for the remaining tree parts (i.e., tree stem) post-treatment in the form of a qualitive pruning or similar.

Table 4. Auxiliary overview of applied harvesting scenarios.

Treatments	Stand and Tree Health	Products		Labour	
		Quality	Quantity	Ease of Implementation	Operation Efficiency
H2	−	+	+	+ +	+ +
H3	− −	+	+ +	+	+
BrO	o	−	−	− −	− −
Di2	− −	+	+ +	−	−
Di7	−	+ +	+	−	+

Levels of influence: very positive (+ +), positive (+), none/negligible (o), negative (−), very negative (− −).

Lastly, we aim to qualify labour effects of the applied treatment. By design, the treatments were devised to reflect current practices in the region but also to suggest a normal and extreme variant. Height treatment reflects treatments that could be carried out from the ground with a hand saw, with and without a ladder, for example. Diameter-based removal of branches is naturally more time-consuming, thus requiring a measurement prior to each cut, in reality this is not carried out, such factors have an influence on each operation's efficiency.

Pari et al. [8] reported a great variability of RSR in tonnes of dry mass pruning residues among crops and within crops in Italy: vineyards, 0.11 to 7.11 t ha^{-1}; olive trees, 0.6 to 7.0 t ha^{-1}; and apple orchards from 1.0 to 9.8 t ha^{-1}. Furthermore, Pari et al. [8] reported average dry pruning yield values at national value: vineyards, 1.15 $\pm$ 0.51 t ha^{-1}; olive trees, 1.90 $\pm$ 1.44 t ha^{-1}; and pome fruit orchards, 1.88 $\pm$ 0.87 t ha^{-1}. For vineyards in Northern and Central Italy, Spinelli et al. [15] found dry pruning yields of 1 $\pm$ 0.28 t ha^{-1} and fresh waste of 2 $\pm$ 0.55 t ha^{-1}, with minor differences between the grape varieties. Assuming a wood density of 500 kg m^{-3} and 25% fresh wood water content, *H3* and *Di2* would have a RSR of 3.66 t ha^{-1} (fresh) and RSR of 2.95 t ha^{-1} (dry). However, commercial pruning operations in orchards do not follow specific size-related criteria but rather a spatial and qualitative focus; thus, such residual biomass will vary greatly due to the subjective nature of the operation with respect to the operator [42], and the specific target, site, and growth conditions.

Exploring more possibilities for AFS production, García-Maraver et al. [11] found annual fresh pruning residues for olive groves in Andalusia (Spain) of 3 t ha^{-1}, from which 0.7 t ha^{-1} wood residues and 1.5 t ha^{-1} branches, and 0.8 t ha^{-1} leaves. Following our approach, pruned foliage biomass could be estimated with the QSMs by using leaf insertion algorithms [23,43], quantifying the leaf area of branches, and converting to biomass. Furthermore, Sagani et al. [12] had an annual fresh pruning yield of 15 kg $tree^{-1}$ for olive trees in Greece. Likewise, Pérez Arévalo and Velázquez Martí [13] quantified the dried pruning biomass of 16.93 $\pm$ 9.15 kg $tree^{-1}$ for teak trees in the Province of Guayas (Ecuador). Our study verified theoretical yields of 34.2 $\pm$ 49.8 kg $tree^{-1}$ (fresh) for *H3* and *Di2* and 27.4 $\pm$ 39.9 kg $tree^{-1}$ (dry).

Unlike the cited studies assessing annual biomass yields, our branch harvesting simulations were one-time interventions. The future tree and stand development are uncertain and can influence the biomass production ratios. Reducing occlusion of tree point clouds would require a regular scanning step lower than 10 m [44], which would decrease the occlusion of canopies, increase the precision of the assessment in terms of more outstanding branch orders ($\geq$3), and reduce the uncertainty of other QSM-derived attributes. While modern TLS sensors can derive additional characteristics for each laser measurement, which is helpful for point classification (e.g., reflectance), division between wood and leaf points is also achieved by specific algorithms [45].

An assessment of wood or biomass yields through TLS data and QSMs has many advantages: it is a non-invasive technique, enables the evaluation of harvesting strategies and different outputs, is a unique possibility of quantifying the resultant material in comparison with the tree or stand structure, and, it enables the evaluation of the operation efficiency while assisting cost assessment. Drawbacks are the inherent expense and, thus, availability of TLS scanners and computational resources, including trained personnel for data collection and analysis. Nevertheless, such an approach could be applied to situations of highly appreciated AFS tree products, in the conversion of tree plantations to AFS, and for the exploitation of woody resources without felling trees (e.g., urban trees). More-uniform landscapes ease data collection, and leaf-off conditions facilitate and speed up the reconstruction of tree structures. Hence, the more multi-stratified an AFS, the more complex the 3D approach.

5. Conclusions

The approach presented here can assess branch wood supply, mitigating biomass procurement while keeping multifunctional trees in agroforestry systems. Assuming low-mechanised harvesting scenarios, we estimated wood yields for different harvesting simulations, gathered information on the operations, retained and removed woody resources, and evaluated assortments. Such a technique has the potential to become widely used in the future, supporting the management of agroforestry systems and optimising their provisioning services.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/f13050650/s1, Supplementary Files S1 and S2. Figure S1: Individual tree point clouds identified by colours (up), leaf-on mode evidenced by intensity values (middle), and the leaf-off point clouds (bottom); Figure S2: Stand-level wood assortments available in linear meters for each simulated harvesting treatment; Figure S3: Boxplots of the absolute branch volume removal in each harvesting simulation with the red crosses representing treatment means; Table S1: QSM-derived tree parameters for trees in the stand (n = 66); Table S2: Optimised QSM input parameters for each tree; Table S3: Summary of available assortments and yields per harvesting treatment. Supplementary File S2 contains the assessment of assortments on a tree basis for each harvesting simulation.

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