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The Effects of
Tree-Alfalfa Intercropped Systems
on Wood Quality in Temperate Regions

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1. Introduction

Agroforestry is a dynamic, ecologically based, natural resource management system that, through the integration of trees in farm and rangeland, diversifies and sustains production for increased social, economic and environmental benefits (Leakey, 1996). Apart from the social and cultural advantages of growing trees, recreational benefits for human being, as well as improvement in wildlife, there are other advantages associated with planting trees with crops. There are five mechanisms through which trees contribute to the agricultural environment (Yin, 2004). These include reducing wind velocity and wind erosion, controlling sheet and rill erosion, mediating solar radiation and regulating soil and air temperatures, increasing field moisture, and improving soil nutrients.

In low forest cover countries, development of tree-based intercropping is necessary to reduce the dependence on natural forests. Such an agroforestry system can encourage farmers to produce wood along with annual crops (Efhami Sisi et al., 2010). However, a tree plantation is usually considered a long-rotation activity in comparison with agricultural crops. This discouraged farmers from adopting tree farming (Asadi, 1994). Agroforestry encompasses several systems; among which alley intercropping is considered a common practice in this regard. More than 40% of research projects in international agroforestry research institutes focus on this practice (Singh et al. 2001).

Alley cropping is an agroforestry management system that permits the production of a variety of crops in alleys between widely spaced rows of trees (Asadi et al., 2005). Alley cropping (hedged agroforestry) increase tree cover, fuelwood supplies and infiltration of rain, provide protection against wind, and reduce runoff (Otengi et al., 2000). In alley cropping systems where timber is a major ecosystem service, initial spacing between the trees is of great importance because it influences anatomical, physical, and morphological characteristics of wood. For woody components in agroforestry systems, there are some desirable characteristics, such as adaptability, straight bole, thin crown, appropriate leafing phenology, deep root, little or no negative effect on crop, and economical and social traits (Muthuri et al., 2005; Singh et al., 2001). Interplanting of trees with crops requires management practices, which affect wood characteristics of timber trees in alley cropping.

However, little is known about the properties of timber sourced from agricultural lands (Shanavas & Kumar, 2006).

In agroforestry systems, farmers are interested in increasing initial spacing between trees to achieve higher crop yields. Two factors are considered of vital importance in an alley agroforestry to study the quality of the wood cultivated: the crops and their effects on the soil fertility and tree growth, and the initial spacing between the trees. DeBell et al. (2002) found that interplanting nitrogen-fixing *Albizia* spp. increased the mean stem diameter of *Eucalyptus saligna* by 37% but did not alter wood density. Similarly, growth rate of trees generally increases with wider initial-spacing because of the decreased competition with surrounding trees for soil moisture and nutrients (Wodzicki, 2001). The goal of silvicultural practices such as thinning, spacing, interplanting, weeding, and fertilizing is to increase tree height and diameter growth (Chen et al., 1998). In turn, any change in the growth pattern and growth rate of a tree may result in wood property variation (Zobel & van Buijtenen, 1989).

All forestry practices may influence tree growth in one way or another, and consequently, wood properties would also be altered (Fig. 1). It should be justified if the changes in wood properties such as the size of log, proportion of juvenile wood, density, fiber length, etc., are technically accepted by the wood industry. The economical aspects of the silvicultural practices should also be taken into account (Bowyer et al .2007).
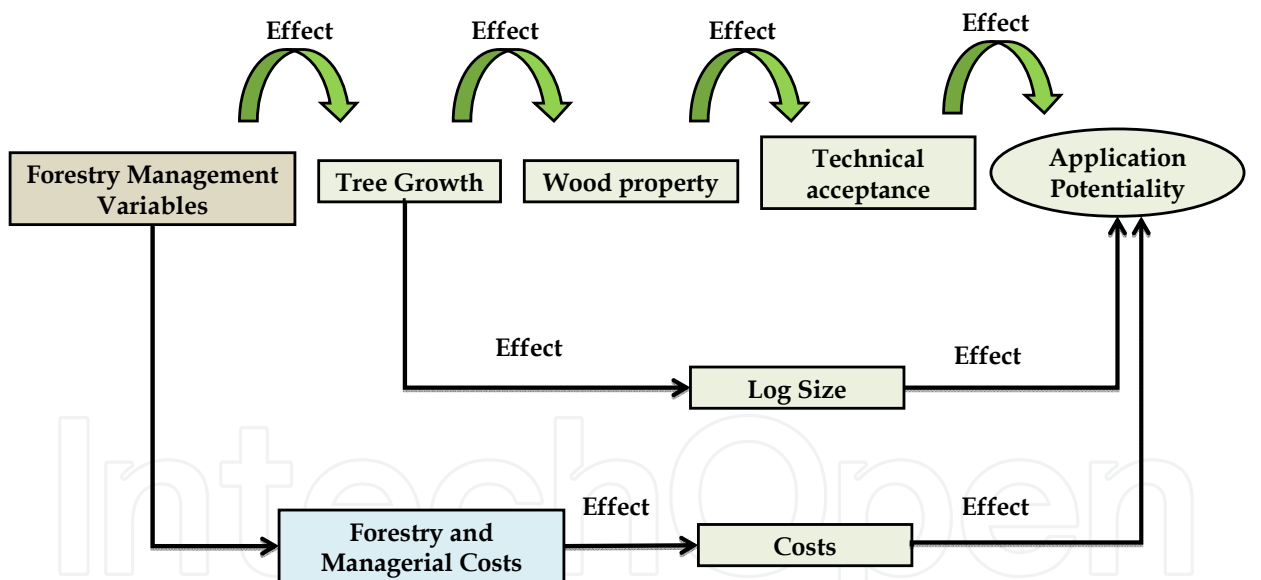

Fig. 1. Relationship between silvicultural practices and its effects on wood quality (Bowyer et al., 2007)

The influence of growth rate on wood quality is very complicated. In many cases, a tree species may be positively affected by a certain forestry practice that shows a completely opposite effect on another species (Kollmann & Cötè, 1968). For example, increase in growth rate of a tree may cause some changes in tree ring structures (Fig. 2). In softwoods, increase in tree ring width does not have any effect on dense latewood width; it would therefore be predicted that the density of wood would naturally decrease. In ring-porous hardwoods such as oak, this effect would be quite the opposite; that is, increase in tree ring width does

not have any effect on porous early wood width; therefore, the density would naturally increase. In diffuse-porous hardwoods such as poplar, however, no clear relationship between ring width and wood density is observed (Kollmann & Cötè, 1968). Similarly, growth rate may have significant effects on wood anatomy (Efhami Sisi et al. 2010, 2011a), physical and mechanical properties (Taghiyari & Sarvari Samadi, 2010; Taghiyari, 2011; Taghiyari et al., 2010, 2011; Taghiyari & Efhami Sisi, 2011; Shanavas & Kumar, 2006). Some researchers believe that, regardless of the cause of increase in growth rate, it may have similar effects on wood quality (DeBell et. al., 1998).
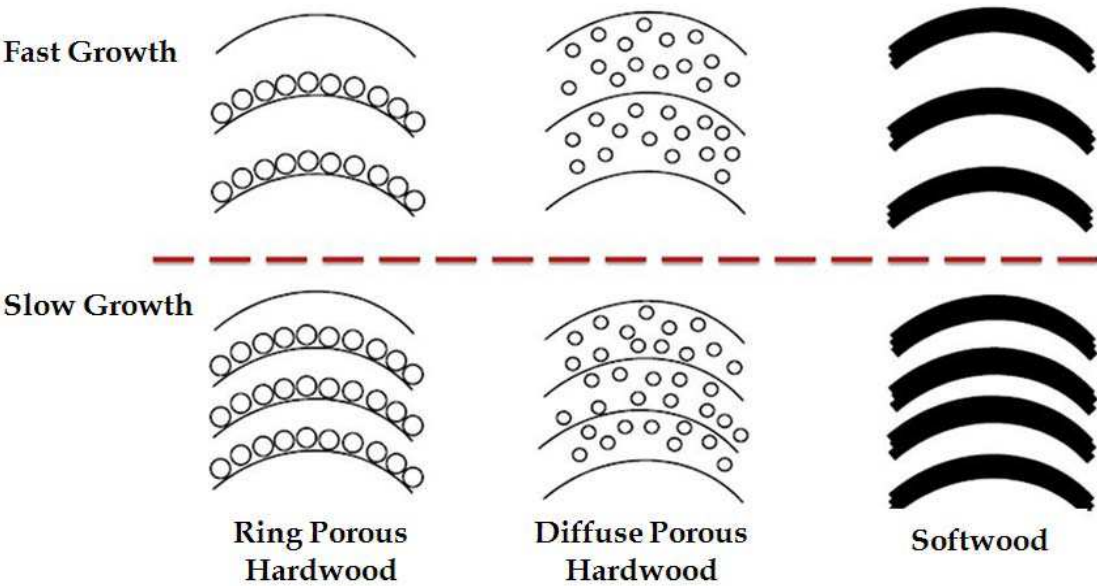

Fig. 2. Schematic diagram of growth rate effects on tree ring structure

There are many complicated interactions between wood properties and technical acceptance that need to be taken into account when studying growth rate effects on wood quality. Improvement in tree growth properties should not necessarily have similar results on technical acceptance of the wood (Fig. 3). In ring-porous species for instance, increase in density by higher growth rates would ultimately improve mechanical properties; while increase in diameter and the number of branches showed negative effect on it (Zobel & van Buijtenen, 1989).
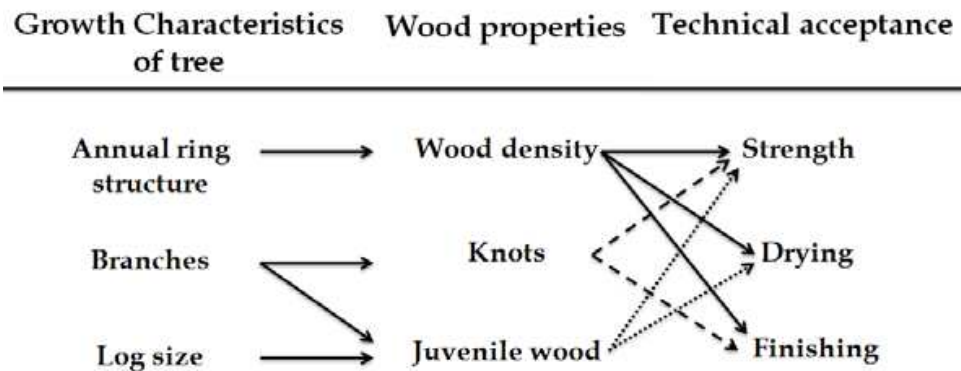

Fig. 3. Effects of tree growth characteristics on wood quality and technical acceptance (Zobel & van Buijtenen, 1989)

Based on the above literature review, alley cropping and N-fixing crops improve the growth rate of trees. Changes in growth rate by forestry management variables (Fig. 1) are reported to alter wood properties. However, not many studies have so far assessed the extent to which alley cropping would affect wood properties from anatomical, physical, and mechanical points of view. Therefore, this chapter evaluates the effects of initial spacing and intercropping on growth rate and wood quality.

2. Effects of agroforestry on growth rate and bole form

Increases in soil organic matter and total organic nitrogen are reported to explain the increase in growth rate of trees in agroforestry systems (Eaglesham et al. 1981; Sea-Lee et al. 1992). DeBell et al. (2002a) evaluated the effects of chemical fertilizer, spacing, and interplanted nitrogen-fixing trees on diameter growth of 15-year-old *Eucalyptus saligna* trees and concluded that diameter growth (hence, productivity) can be increased substantially through supplemental nitrogen and increased growing space. In a separate study, 8 years after establishment, *P. deltoides* intercropped with wheat-fodder maize had larger diameter, crown width and wood volume (m³/ha) than pure tree stands (Chaudhry et al., 2003). Other studies have also shown that (i) an intercropped agroforestry system was more economical at the rotations of 4 and 6 years compared to pure stands (Chaudhry et. al., 2003), (ii) there was more growth in poplar trees under agroforestry conditions than that of forest conditions (Singh et al., 1988), and (iii) *Acacia auriculiformis*, *Acacia mangium*, and *Grevillea robusta* trees grown in agroforestry systems had better growth rate (Shanavas & Kumar, 2006).

Efhami Sisi et al. (2008) studied the effects of *Populus nigra*-alfalfa intercropping and initial spacing on growth rate of poplar trees. They found that (i) tree diameter in tree-crop intercropped systems was greater than in pure tree stands, and (ii) tree diameter increased with decreasing tree density. General trends of diameter growth in relation to age were similar for all treatments (Fig. 4), but the greatest difference in diameter growth values occurred from age 3 to about age 7.
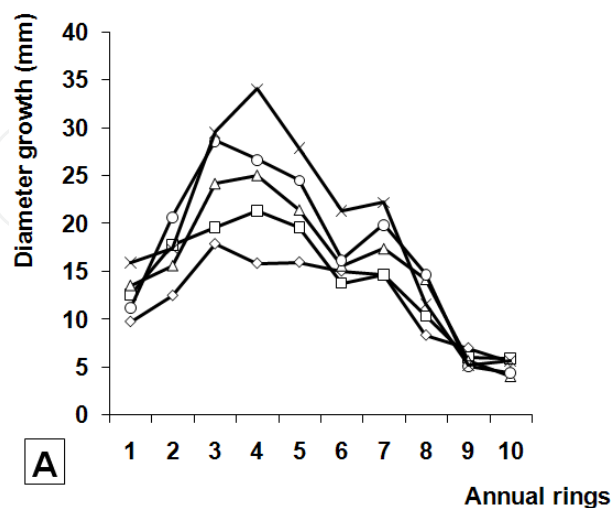

Fig. 4. Diameter growth as a function of ring number from pith to bark
◊ = 3 m × 4 m without alfalfa; □ = 3 m × 4 m with alfalfa; Δ = 3 m × 6.7 m with alfalfa;
○ = 3 m × 8 m with alfalfa; × = 3 m × 10 m with alfalfa

With regard to the early rising and the consequent falling trend of tree growth (Fig. 4), in any plantation, the ring width generally decreases with age because of the increased competition with the surrounding trees (Wodzicki, 2001); in poplar plantations, this decrease in ring width is usually observed in rings 3 to 5. The pointer year at age 6 found only in trees of the treatments with alfalfa might be due to the termination of alfalfa cultivation at age 5 which could be beneficial to trees (Fig. 4).

Alfalfa, a nitrogen(N)-fixing plant, has the capacity of fixing about 230 kg N ha^{-1} yr^{-1} and does not need annual plowing and sowing (Tisdal & Nelson, 1974). In tropical and sub-tropical forests, trees of legume family such as *Albizia*, *Pterocaria*, and *Gleditchia* spp are the main source for N-fixing in the soil (Tisdal & Nelson 1974).. Use of N-fixing plants is one of the methods for fertilizing plantation trees (Zobel and van Buijtenen, 1989). Legumes have the synergistic effect of improving soil health through biological N-fixation and adding nutrient-rich residues to the soil (Skelton, 2002). Intercropping trees with alfalfa may increase in soil N content and fertility resulting in an increase in tree diameter (Saarsalmi et al., 2006; Skelton, 2002; Tisdal & Nelso, 1974). Moreover, a wider initial-spacing would decrease competition among individual trees (Wodzicki, 2001) and consequently increase growth rate. Overall wood production and basal area can decrease although wider initial spacing increases growth rate. While intercropping trees with alfalfa can increase basal area, wider initial spacing could decrease it (Fig. 5).
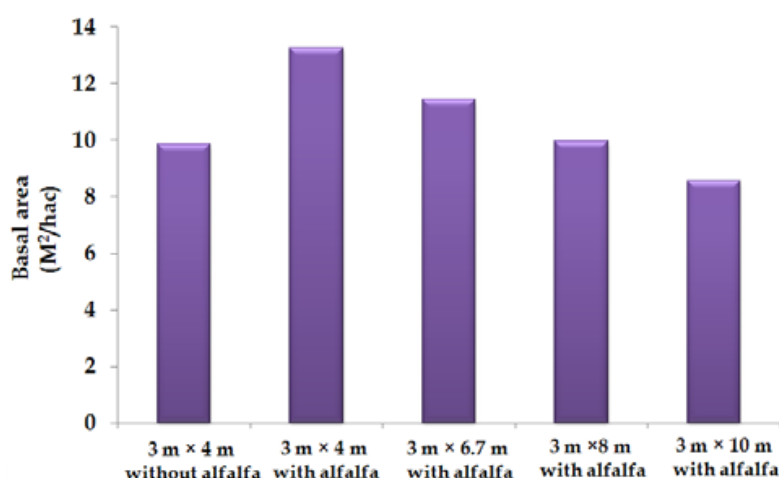

Fig. 5. Basal area of poplar trees influenced by initial spacing and alfalfa-intercropping (Efhami Sisi et al., 2008)

Although the trees in plantations with wide initial spacing grew at a significantly rapid rate and quickly reached merchandisable diameter, the increase in growth rate of trees did not compensate for low tree density (Lundgren, 1981). There is always an optimum initial spacing for a certain tree species - given specific climatic conditions and stand quality in which biomass does not change with initial spacing. Sjolte-Jorgensen (1967) presented data showing quality trends for Norway spruce (Table 1). The biomass of 47-year-old Norway spruce did not change between 2 m and 3 m spacing regimes while mean diameter of trees increased. In fact, this is an optimum initial spacing in which rapid growth rate and wider initial spacing may compensate for a lower tree-density. Finding this optimum point is of great importance in agroforestry system. Larger diameter logs yield significantly more revenue than smaller logs (Barbour and Kellogg's, 1988).

Spacing (m)	Mean Diameter (cm)	Taper Whole stem (cm/m)	Percentage of Knots	Total Production (Tones/ha)
1.25 × 1.40	20.1	0.98	0.191	261
1.40 × 1.65	20.5	1.02	0.236	240
2.00 × 2.00	24.1	1.04	0.260	218
3.00 × 3.00	26.0	1.13	0.340	218
3.50 × 3.50	28.3	1.26	0.335	166

Table 1. Stand characteristics of 47-year-old *Picea abies* as influenced by initial spacing (Data cited in Sjolte-Jorgensen 1967)

Table 1 shows that initial spacing could influence bole quality; that is, an increase in initial spacing could decrease bole quality because of a higher percentage of knots and taper. Trees with significant taper have relatively low lumber yields and they are unacceptable for manufacturing some of the specialty products such as poles. Knot size is an important factor for poles and lumber. The greater the proportion of knots, the lower the strength and the lower the value of clear wood produced (Zobel & van Buijtenen, 1989).
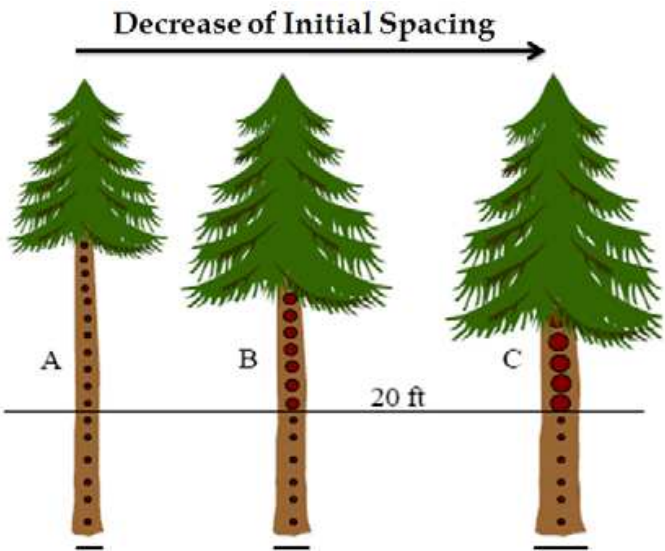

Fig. 6. Schematic diagram of the effects of initial spacing on crown and branch expansion

Taper is largely a crown effect. Since the cambium activates first within the crown, growth rings tend to be widest here, and maximum diameter growth often occurs. Thus, trees with large crowns tend to have highly conical stems, while stems of trees whose crowns have receded gradually become more cylindrical (Fig. 6). High-taper trees have smaller scaling diameters (because diameter is measured at the log's small end). Knot size is directly impacted by crown size. Persistent, live crowns give branches more time to grow, and knot size increases. Receding crowns limit branch size, thus limiting knot size (Ballard & Long, 1988).

Efhami Sisi et al. (2008) studied the effects of initial spacing and intercropping (with alfalfa) on bole form factors such as taper, eccentric, roundness and number, diameter, length and angle of branches, as well as height of trees (Table 2).

| Treatments | Taper (cm/m) | Eccentric | Roundness (%) | Branches | | | | height |
				Number	Diameter (cm)	Length (m)	Angle	
3 m × 4 m without alfalfa	1.37	6.17	1.10	11	3	3.4	40	10.8
3 m × 4 m with alfalfa	1.34	8.9	1.09	12	4	4.2	40	11.8
3 m × 6.6 m with alfalfa	1.42	8.63	1.10	12	4	4.3	45	11.8
3 m × 8 m with alfalfa	1.59	13.63	1.38	12	4.6	5	45	12.1
3 m × 10 m with alfalfa	1.76	11.83	1.28	13	5.6	6	47	12.9

Table 2. Bole form of poplar trees influenced by initial spacing and alfalfa-intercropping (Efhami Sisi et al., 2008)

There was no significant difference in tree height across treatments. Taper, eccentric and roundness increased with increasing inter-tree spacing, while integration of alfalfa did not. Number, length, diameter and angle of branches increased in widely spaced and intercropped treatments. Roundness is also considered as an important and influential parameter of yield in veneer and plywood industries (Mäkinen, 1998). Stand density and thinning accounted for 2 – 9% of roundness (Mäkinen, 1998). Also, eccentricity is considered a sign of reaction wood formation in tree stem. Its measurement was based on maximum radius and minimum radius at breast height, showing an increase by initial spacing (Efhami Sisi et al., 2008).

At a close spacing, the sample trees had somewhat less branches in a whorl than more in widely spaced plots. The most pronounced effect of initial spacing was the increase in branch diameter with increasing initial spacing (Mäkinen & Hein, 2006; Ulvcrona et al., 2007). The effects of initial spacing on straightness of tree bole, diameter, and number of branches in each inter-node, are more pronounced than on intrinsic wood properties (Malinauskas, 1999). Planting trees in widely spaced plots reduces establishment costs and accelerates diameter growth of individual trees, resulting in larger, but fewer, trees at any given age with lower bole quality. The more trees established per acre, the higher the total cubic-foot volume yield. However, this increased volume must be harvested from more and smaller trees (Lundgren, 1981).

3. Effects of agroforestry on wood anatomy

3.1 Vessel properties

Vessel diameter and frequency in trees affect wood quality traits such as permeability which in turn determines, among other variables, wood preservation, wood drying, pulp and paper making (Chen et al., 1998). Efhami Sisi et al. (2010) studied the effects of intercropping *Populus nigra* with alfalfa and initial tree spacing on vessel element attributes by measuring the proportion of each ring relative to the whole disc area to obtain weighting coefficient for every growth ring. The study showed that intercropping *Populus nigra* with alfalfa and increasing initial spacing increased vessel diameter and frequency; while wider initial

spacing decreased the vessel frequency (VF), and to some extent the vessel lumen area percentage (VLA %), but increased vessel lumen diameter (VLD) (Table 3; Figs. 7 & 8).
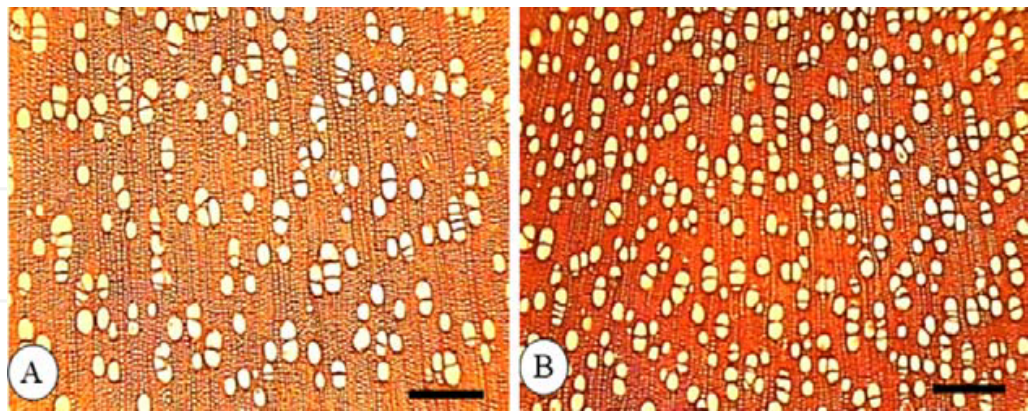

Fig. 7. Microscopic images of cross-section of the third tree-ring in trees harvested in 3 × 4 and 3 × 10 meter inter-tree spacing in tree- alfalfa intercropping (scale bar: 300µ). **A:** 3 × 10 with alfalfa: vessels with low frequency but more diameters resulting in lower vessel lumen area. **B:** 3 × 4 with alfalfa: vessels with more frequency but lower diameter resulting in high vessel lumen area

Vessel lumen diameter increased more or less linearly from pith to bark in all treatments (Fig. 8-A). The rate of increase of VLD in the outer rings was comparatively lower in tree stands without alfalfa than in tree-alfalfa intercropped systems. Vessel Frequency per unit area (mm²) decreased as cambial age increased (Fig. 8-B), but rates were similar across treatments. Vessel Lumen Area (%) increased consistently from pith to bark in treatments with alfalfa (Fig. 8-C). Zobel and van Buijtenen (1989) reported that N fertilization increases the period of juvenile wood production. Considering the definition of juvenile wood as the part of wood that shows severe radial change in wood properties (Zobel & Sprague, 1998), it may be expected that intercropping trees with alfalfa may increase the period to reach wood maturity.

Treatments	Annual Diameter Growth (mm)	Based on the area of tree rings		
		Vessel Diameter (µm)	Vessel frequency per mm	Vessel lumen area percentage
3 m × 4 m without alfalfa	12.2 (d)	62 (c)	94 (b)	28 (b)
3 m × 4 m with alfalfa	13.8 (cd)	67 (b)	103 (ab)	35 (a)
3 m × 6.7 m with alfalfa	14.9 (bc)	69 (ab)	90 (ab)	33 (ab)
3 m × 8 m with alfalfa	16.4 (b)	68 (ab)	89 (ab)	33 (ab)
3 m × 10 m with alfalfa	19.3 (a)	72 (a)	79(a)	32 (ab)

( ) Duncan's separation grouping results

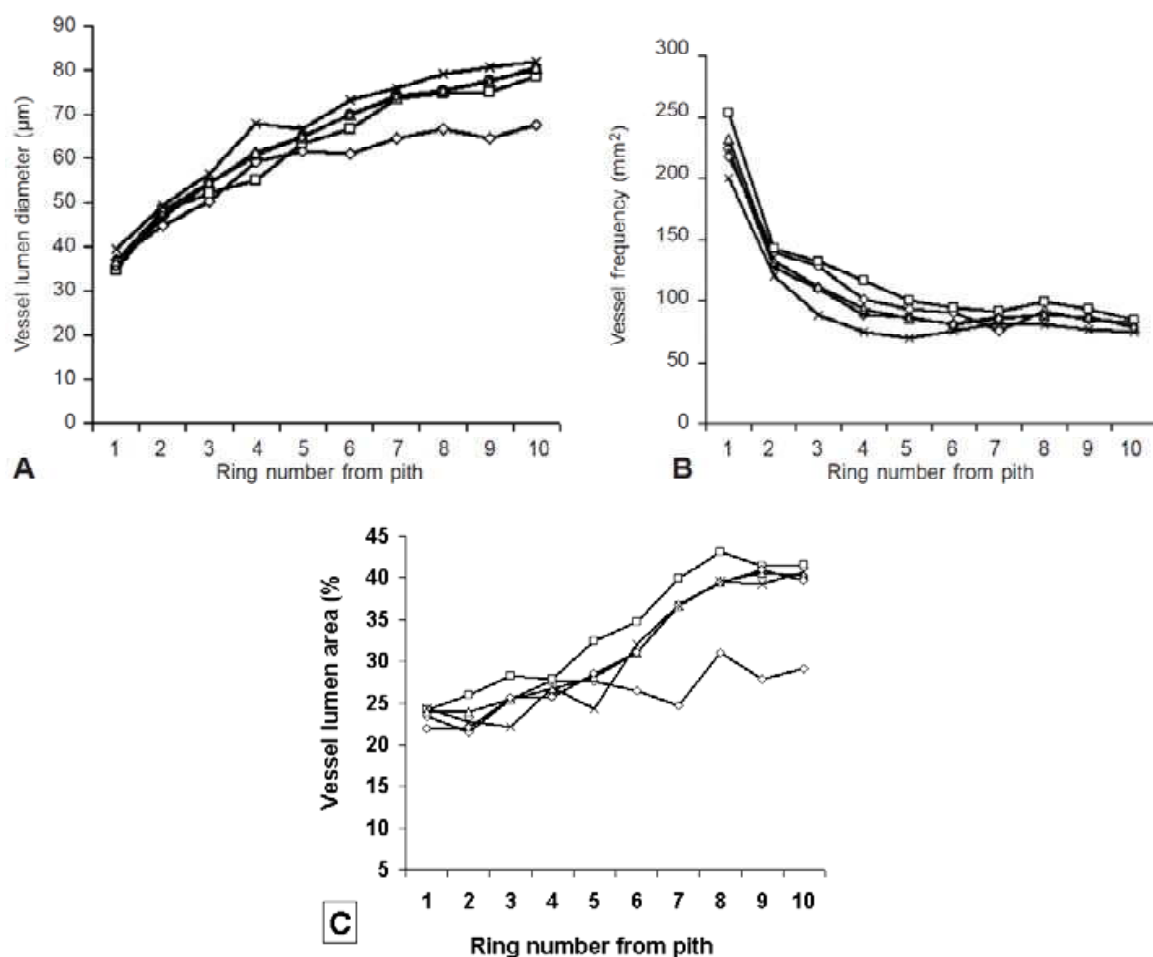Table 3. Mean values for annual diameter growth rate and vessel properties of poplar trees

Fig. 8. Radial dimensions of vessel lumen diameter, vessel frequency, and vessel lumen area as a function of ring number from pith to bark in young poplar trees after different treatments; ◊ = 3 × 4 without alfalfa; □ = 3 × 4 with alfalfa; Δ = 3 × 6.7 with alfalfa; ○ = 3 × 8 with alfalfa; × = 3 × 10 with alfalfa; A= Vessel lumen diameter; B= Vessel frequency in mm2; C= Vessel lumen area percentage

Although agroforestry systems were found to have positive effects on growth rate, no correlation was found between growth rate and wood properties of six-month-old poplar stems (Jourez *et al.* 2001). However, Doungpet (2005) reported a positive correlation between growth rate (ring width) and vessel lumen diameter (VLD), but negative correlations with VF. Peszlen (1993) investigated three different clones of 10- to 15-year-old poplars and reported that wood properties had no consistent and significant relationship with growth rate. Arnold and Mauseth (1999) reported that low N fertilizer caused reduction of VLD and VF in the cactus species *Cereus peruvianus*. In *Populus deltoides*, deficiencies of nitrogen and sulfur resulted in reduced fiber and vessel diameter (Zobel & van Buijtenen, 1989). These studies suggest that agroforestry systems have the potentiality to significantly affect wood properties.

3.2 Fiber properties

Fiber attributes in trees determine, to some extent, the final quality of pulp and paper (Dinwoodie, 1965). Efhami Sisi et al. (2011a), studying the effects of intercropping *Populus*

nigra with alfalfa and initial tree spacing on fiber element attributes, found that fiber diameter and wall thickness significantly increased in tree harvested from tree-alfalfa intercropped plots (Table 4). However, initial-spacing had no significant effect on fiber properties.

Cluster analysis on fiber wall thickness and fiber diameter showed that all three trees of treatment without alfalfa are clustered together (Fig. 9). Although results of Duncan test on fiber length showed the treatment without alfalfa is grouped quite separately, individual trees of this treatment were clustered differently. Also, different trees of treatments with alfalfa were clustered separately. Fiber lumen diameter was not significantly different among treatments. Consequently, fiber wall thickness was the main source of fluctuations in fiber diameter (Table 4).

Table 4 shows that (i) tree diameter and fiber morphological properties of poplar trees in poplar-alfalfa intercropped plots were significantly greater than those in pure poplar stand at all initial tree spacings, (ii) properties of trees in intercropped systems were not significantly different across different initial inter-tree spacings. Therefore, tree-alfalfa intercropping, rather than initial spacing, determined fiber properties in these agroforestry systems.

Treatments	Tree Diameter (cm)	Fiber length (μm)	Fiber wall thickness (μm)	Fiber lumen diameter (μm)	Fiber diameter (μm)
3 m × 4 m without alfalfa	11.4 (c)	895.3 (b)	3.19 (b)	16.8 (ab)	22.2 (b)
3 m × 4 m with alfalfa	14.5 (b)	936.7(ab)	3.91 (a)	17.1 (a)	24.4(a)
3 m × 6.7 m with alfalfa	17.2 (ab)	958.9 (a)	3.88 (a)	17.1 (a)	24.8 (a)
3 m × 8 m with alfalfa	17.5 (ab)	961.0 (a)	3.87 (a)	16.5 (a)	24.9 (a)
3 m × 10 m with alfalfa	18 (a)	957.8(a)	3.93 (a)	16.4 (a)	24.7 (a)

Table 4. Mean values for diameter and fiber morphological parameters of poplar

Fiber length in all treatments increased rapidly from pith to bark. However, fiber diameter and wall thickness showed mild fluctuation (Figs. 10-A & B). The treatment without alfalfa showed a slightly less steep, but still significant, increase in fiber attributes, especially in fiber length. As to the milder changes of fiber attributes in treatment without alfalfa, and considering the definition of juvenile wood as the part of wood that shows severe radial changes in wood properties (Zobel & Sprague, 1989), it may be concluded that intercropping with alfalfa may increase the period to reach wood maturity. However, final decision would be made when older trees are studied. Similar results were also found in vessel attributes of the same treatments (Efhami Sisi et al. 2010). Zobel & Van Buijtenen (1989) reported that nitrogen fertilization increases the period of juvenile wood production. Therefore, it is expected that those trees obtaining more nitrogen would show a more intensified increase in their fiber-length trend.
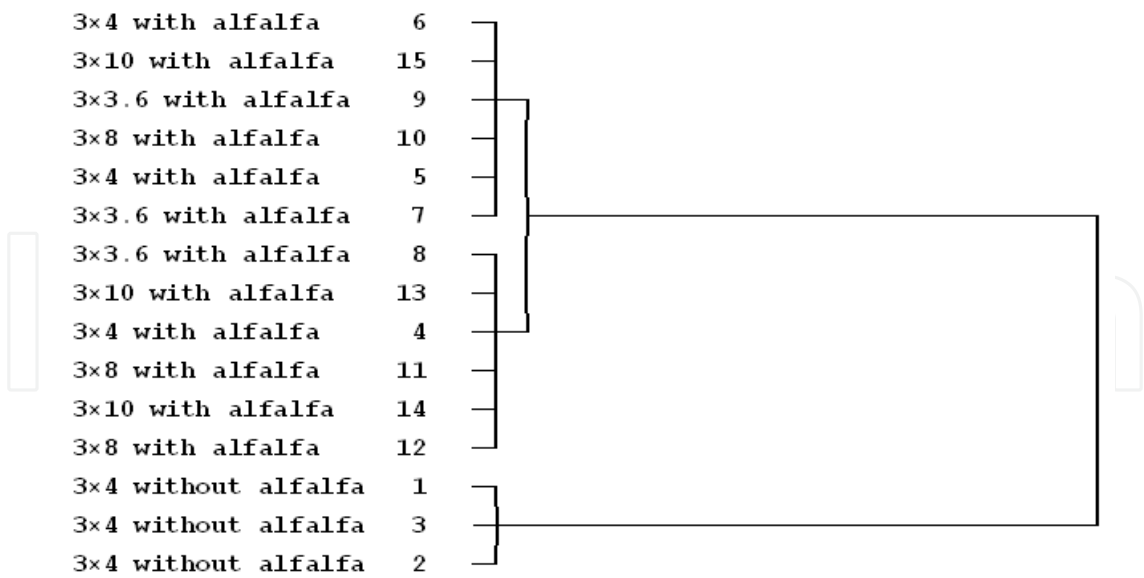
```
3×4 with alfalfa       6  ─┐
3×10 with alfalfa     15  ─┤
3×3.6 with alfalfa     9  ─┤
3×8 with alfalfa      10  ─┤
3×4 with alfalfa       5  ─┤
3×3.6 with alfalfa     7  ─┤
3×3.6 with alfalfa     8  ─┤
3×10 with alfalfa     13  ─┤
3×4 with alfalfa       4  ─┤
3×8 with alfalfa      11  ─┤
3×10 with alfalfa     14  ─┤
3×8 with alfalfa      12  ─┘
3×4 without alfalfa    1  ─┐
3×4 without alfalfa    3  ─┤
3×4 without alfalfa    2  ─┘
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Fig. 9. Cluster analysis of all 15 trees based on wall thickness of fibers

Fig. 10. Mean characteristics as a function of ring number from pith to bark. **A**: Fiber length; **B**: Fiber diameter; **C**: Fiber wall thickness; **D**: Ring area. ◊ = 3 m × 4 m without alfalfa; □ = 3 × 4 with alfalfa; Δ = 3 × 6.7 with alfalfa; ○ = 3 × 8 with alfalfa; × = 3 × 10 with alfalfa

Efhami Sisi et al. (2011) observed that the whole-disk fiber length increased with growth rate caused by agro-silvicultural practices as correlated by stem diameter (Fig. 11-A).

Furthermore, weighted fiber diameter and wall thickness showed an increasing trend by stem diameter (Fig. 11-B and C).

Focusing on a positive relationship between whole-disk fiber attributes and growth rate, DeBell et al. (1998) and Doungpet (2005) found that fast-growing trees have more of their basal area concentrated in rings further from the pith than do slower growing trees, and these rings have longer and thicker fibers compared with rings closer to the pith. Thus, whole-disk fiber attributes increased with overall growth rate. Therefore, under similar conditions and with the same age and species, fast-growing young trees have longer and thicker fibers.

A negative effect of growth rate on fiber length was expected, given the existing knowledge about lateral divisions and how they may affect the length of cambial initials, i.e., high rate of anticlinal division is accompanied by short cells (Bannan, 1967). It has been proposed that the cell length in juvenile wood is related to age (Fujiwara & Yang, 2000). However, most of relationships between growth rate and fiber length were not significant at the earlier ages; at the older ages, although some significant relationships were observed, but there were not outstanding (Table 5).
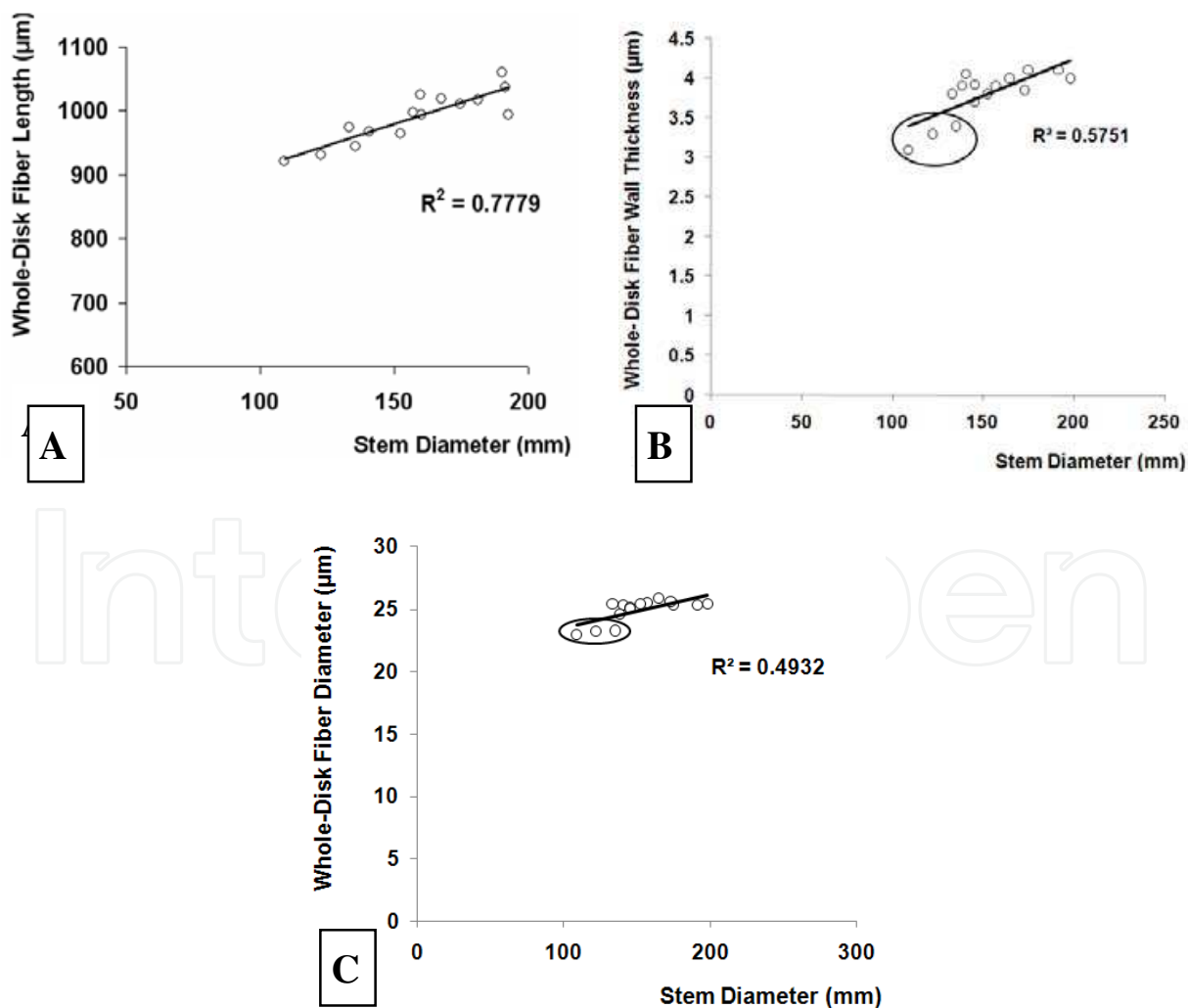

Fig. 11. Mean whole-disk fiber attributes as a function of stem diameter

	Ring 1	Ring 2	Ring 3	Ring 4	Ring 5	Ring 6	Ring 7	Ring 8	Ring 9	Ring 10
Significance level	0.128 NS	0.154 NS	0.018 NS	0.012 NS	0.046 S(+)	0.278 NS	0.008 S (+)	0.076 NS	0.030 S(-)	0.461 NS
R square	0.169	0.150	0.209	0.193	0.273	0.190	0.326	0.222	0.315	0.046

S Statistically significant at the 5% level.
NS Not significant at the 5% level.
( ) positive (+) or negative (-) correlation

Table 5. Regressions analysis results for correlations between ring width and fiber length (Efhami Sisi et al., 2011a)

The effect of growth rate on shortening the cambial initials would be overshadowed by the subsequently greater elongation of daughter cells in the fast-growing trees (Fujiwara & Yang, 2000; Debell et al. 1998). For example, daughter-cell elongation of fibers in hardwoods averages 140% (Panshin & deZeeuw 1980). It was reported that fiber length was not influenced by growth rate in poplar plantations that are cultivated under different silvicultural practices and had dissimilar growth rates (Snook et al., 1986; DeBell et al., 2002a). Although intercropping and initial spacing have significant effects on fiber dimensions, their effects on tree growth are more influential (Efhami Sisi et al., 2011a). Also, agro-silvicultural practices increase growth rate; but considering the existing knowledge on lateral divisions and how they may affect the length of cambial initials, this increase in growth rate should not necessarily end up in shorter fiber length in young poplar trees as was previously believed.

Debell *et al.* (1998) found that growth rate under different initial spacing had no consistent effect on fiber length within rings of the same age for rings 2-6 of young poplar hybrids although for ring 7 there were positive correlation. They believed that this general relationship will hold for most cultural practices (e.g., increased growing space and supplemental nutrition) that are applied to enhance growth rate. Fujiwara and Yang (2000) reported that there was a positive relationship between fiber length and ring width in mature wood of *Populus tremuloides* Michx. Koubba et al. (1998) reported the correlation between fiber length and growth rate in poplar hybrids varied over the age of the tree. At early ages, correlation between ring width and fiber length was not significant; at older ages, slight negative but significant correlation was found between these two traits. Other studies reported in cultured poplars have concluded that growth rate have no effect on fiber length (Snook et al. 1986; DeBell et al. 2002b). Despite several studies undertaken to assess the effects of growth rate on fiber dimension, the results have been inconclusive.

Under high-nitrogen exposure, xylem fibers were 17% wider and 18% shorter compared to the low nitrogen treatment, and very significant thickening of the fiber cell walls was also observed throughout the stem of trees receiving the high-N treatment (Pitre et al. 2007). Zoble and Van Buijtenen (1989) concluded that N may reduce cell size, wall thickness and specific gravity in hardwoods and increase volume growth, but no generalizations can be made due to interspecific variations especially in the diffuse porous hardwoods.

4. Effects of agroforestry on wood physical properties

4.1 Density and shrinkage of wood

Concerns regarding the physical and mechanical properties of timber harvested from fast growing tree species have been articulated, still more studies should be done because such data from the agroforestry systems are scarce (Shanavas & Kumar, 2006). Evaluation of the effects of chemical fertilizer, spacing, and interplanted nitrogen-fixing trees on wood density of 15-year-old *Eucalyptus saligna* trees showed that (i) wider spacing increased mean diameter by 34%, (ii) the level of chemical fertilization did not affect wood density, and mean diameter of trees, (iii) interplanting of N-fixing *Albizia* trees increased mean diameter by 37%, but did not alter wood density (DeBell et al., 2002). Pith-to-bark profiles of wood density revealed that trees with rapid growth had more uniform wood density patterns across the radius. They conclude that diameter growth (hence, productivity) can be increased substantially through supplemental N and increased growing space without decreasing wood density. Moreover, rapid growth - whether associated with improved nutrition or increased growing space - will result in wood with a more uniform density from pith to bark.

Shanavas & Kumar (2006) evaluated physical and mechanical properties of *Acacia auriculiformis, Acacia mangium*, and *Grevillea robusta* trees grown in agroforestry systems and suggested that agroforestry practices per se do not exert any negative impact on wood properties. In another experiment, in older pine and spruce trees, wood density was about the same after as before planting lupines. More growth with more earlywood was obtained but also more latewood was formed. In young pine and spruce though, intercropped with lupines, specific gravity of the wood produced declined (Pechmann and Wutz, 1960). Seven years after establishment of Eucalyptus-Leucaena mixtures, in Brazil, showed that there were no major differences in wood density or holocellulose yields of the eucalypts in the mixture although there was growth response (De Jesus et al., 1988).

The effects of intercropping with alfalfa as well as initial tree spacing on physical variations of *Populus betulifolia* wood were also reported (Efhami Sisi et al., in press). Trees were harvested from an agroforestry trial described in details in Efhami Sisi et al. (2010). Wood density and shrinkage were decreased with alfalfa- *Populus nigra* intercropping while increased by initial spacing (Figs. 12 & 13; Efhami Sisi et al., 2011b). In another study, alfalfa-*Populus nigra* intercropping and initial spacing increased vessel lumen diameter (VLD) and vessel lumen area (VLA), resulting in lower density in this treatment. On the other hand, VLA decreased with increase in initial spacing resulting in higher density. Decrease in wood density caused by direct N-fertilizer was also reported in *Eucalyptus globules* and *P. deltoides* (Raymond & Muneri, 2000). Arnold and Mauseth (1999) reported that low nitrogen fertilizer caused reduction of VLD and VF in the cactus species *Cereus peruvianus*. In *Populus deltoides*, deficiencies of nitrogen and sulfur resulted in reduced fiber and vessel diameter (Zobel & van Buijtenen, 1989). Thus, it can be concluded that the decrease in wood density by alfalfa-intercropping resulted in increase in woody cell-lumen and the consequent wood porosity.

Density had a decreasing trend from pith to bark at breast height, showing similarity with the results of other researcher on different poplar species (Karki, 2001; Doungpet, 2005). Low lumen area of fibers and vessels in the early years of tree growth (Peszlen, 1994; Efhami Sisi et al. 2011a, 2010; Efhami Sisi & Sarayeian, 2009), as well as more extractives in this

section of the stem, may have caused this decrease in density from pith to bark (Zobel & van Buijtenen, 1989).
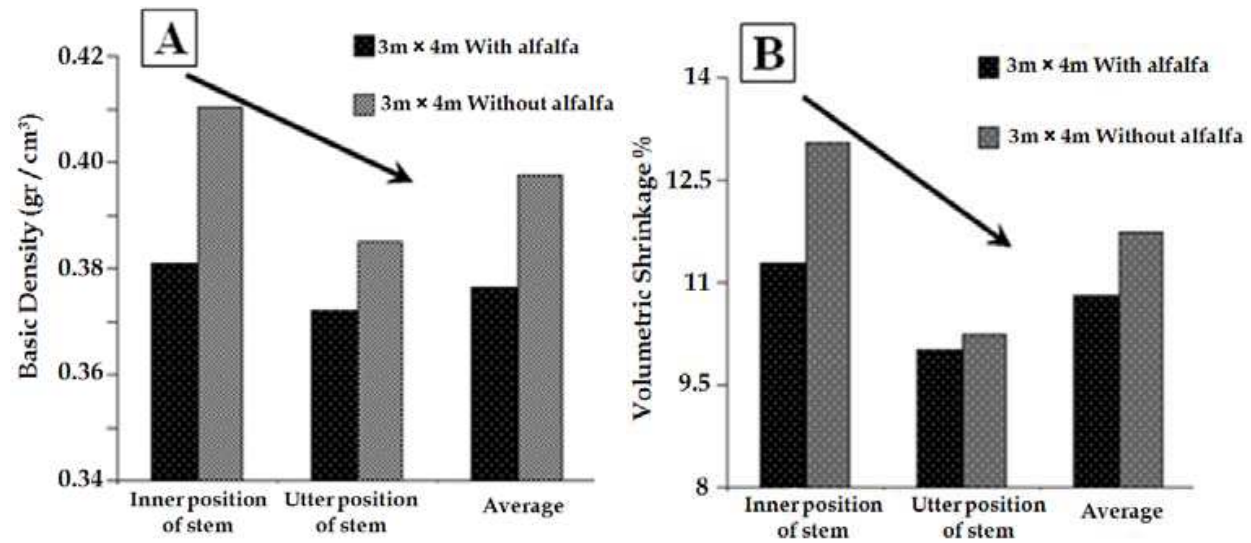

Fig. 12. Density and volumetric shrinkage variations in wood for 3 × 4 meters treatments with and without alfalfa
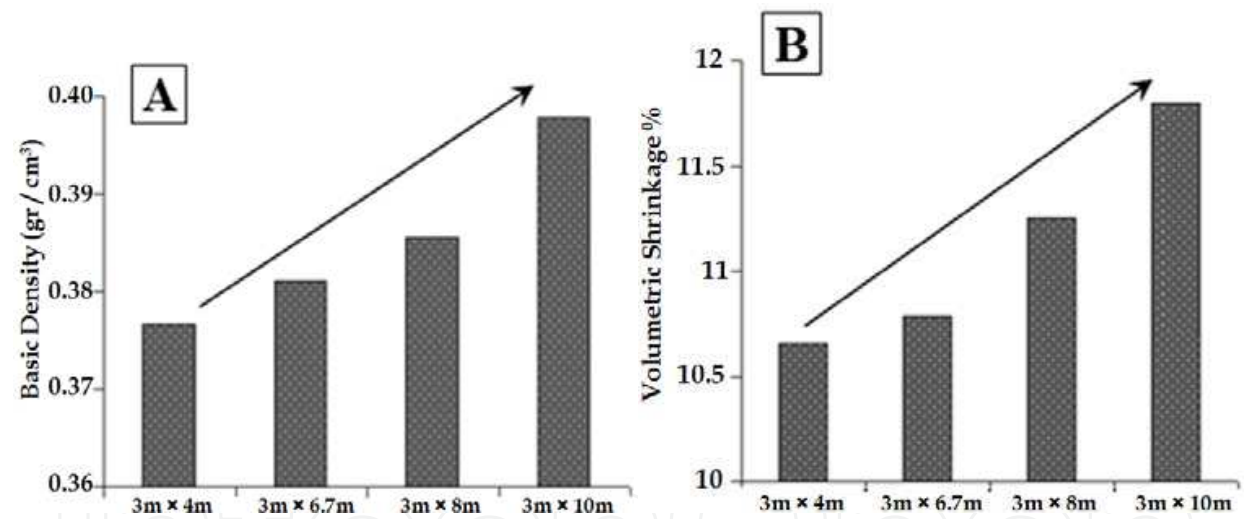

Fig. 13. Density and volumetric shrinkage variations in wood for different initial spacings intercropped with alfalfa

4.2 Permeability of wood

Wood permeability, as a physical property, is of vital importance and has great impact on wood and its utilization in different industries (Chen et al., 1998). Permeability is a critical property of porous materials that have continuous-porosity. Many industries need to know how permeable their porous material is so that they could use permeability values in decision-making processes for impregnation, drying, filtration, as well as other purposes. In hardwoods, longitudinal permeability is more important than transversal (radial and tangential) values because of vessel elements orientation along longitudinal axis of trees (Siau, 1971).

Intercropping and initial spacing significantly influences the vessel properties and capillary structures of wood (Efhami Sisi et al., 2010). Permeability is itself influenced by porosity and capillary structure of wood (Siau, 1995). Thus, the effects of agroforestry practices on permeability were investigated on the same treatments (Efhami Sisi et al., 2010).
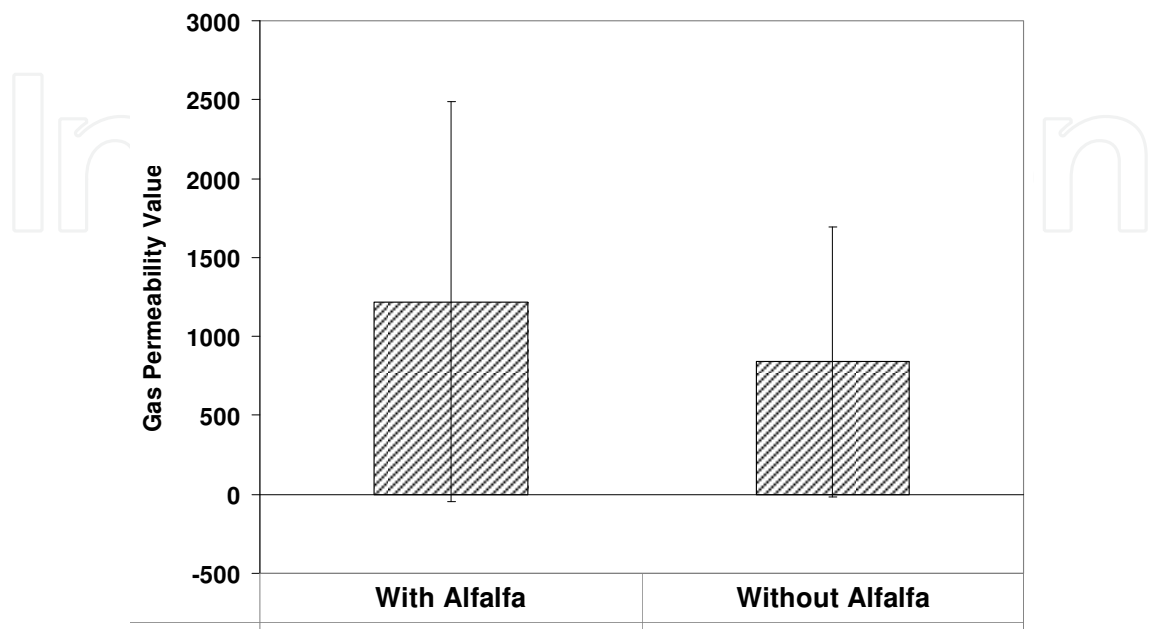

Fig. 14. Specific longitudinal gas permeability values ($\times 10^{-13}$ m^3 m^{-1}) for the two treatments of 3×4 meters with and without alfalfa

Longitudinal gas permeability values for tree stands with, and without, alfalfa were 1,220.4 and 840.2×10^{-13} (m^3 m^{-1}) (Fig. 14), respectively. There were no significant differences ($p < 0.05$) in longitudinal gas permeability between tree stands with and without alfalfa which is characteristic of permeability in solid woods (Taghiyari et al., 2010) (Fig. 14). As to the increase in vessel lumen area and vessel lumen diameter caused by intercropping with alfalfa (Table 3), the increase in permeability could have been expected. Furthermore, wider initial spacing showed an increasing effect on both longitudinal and radial gas permeability (Fig. 15).
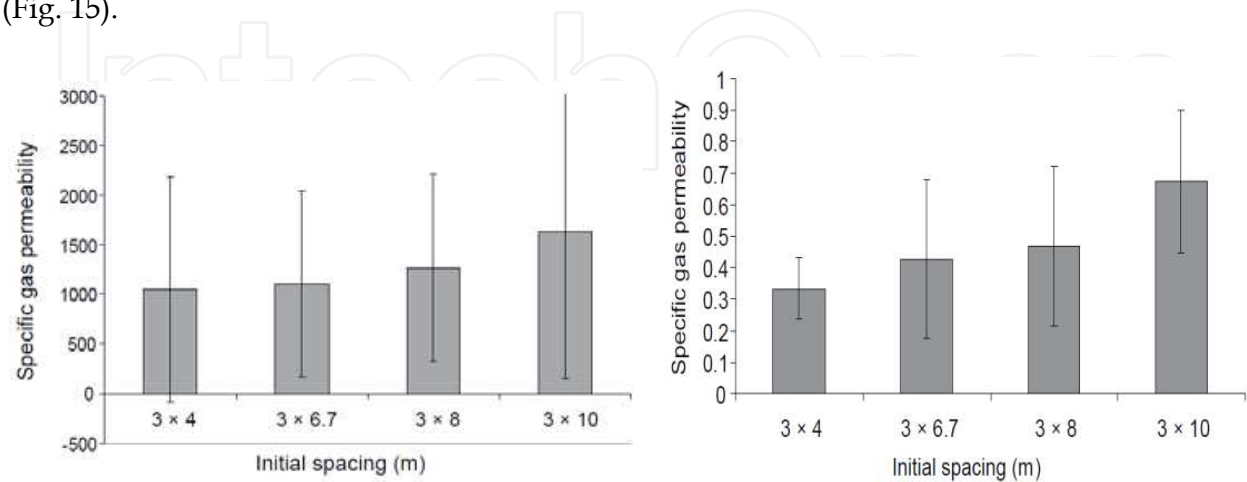

Fig. 15. Specific longitudinal (left) and radial (right) gas permeability values ($\times 10^{-13}$ m^3 m^{-1}) for the four initial spacings intercropped with alfalfa

A study of longitudinal gas permeability at different tree densities in intercropped treatments (Fig. 15) showed significant growth, caused by increase in initial-spacing, increased VLD and naturally gas permeability would be expected to improve. Longitudinal gas permeability increased by as much as 55% from 3×4 to 3×10, but VLD increased by only 7.2%. Poiseuille's law of viscous flow, which applies to gases through hardwood vessels, proves that there is positive relationship between permeability value and the fourth exponent of the radius of capillary (radius of vessels) (Equation 1) (Siau, 1971).

$$k_l = \frac{n\pi R^4}{8\eta} \times 1.013 \times 10^6 \qquad (1)$$

Where:

k_l = longitudinal permeability [cm^3 (fluid) cm^{-1} atm^{-1} sec^{-1}]
1 atm = 1.013×10^6 [dyne cm^{-2}]
R = radius of vessels [cm]
n = N/A = number of vessels per cm^2 of cross section
η = viscosity of fluid [dyne sec cm^{-2}]

The fourth exponent of the radius implies that a slight increase or decrease in vessel radius may have a high impact on gas permeability. A similar conclusion was made for longitudinal gas permeability values in *Populus deltoides* (69/55) and 5 trees of *Populus × euroamericana* (cv. I-214) (Taghiyari et al., 2010). However, VLA decreased by 10.2% from 3×4 to 3×10. But, there is a considerable increase in specific gas permeability (55%). Therefore, VLD had a greater effect on gas permeability than VLA.

Chen et al. (1998) studied correlation between different diameter growth rates caused by tree-tree competition and percentage of vessel lumen area (VLA%) in hardwoods, and found no significant correlation in three hardwoods (northern red oak, black walnut, and yellow poplar). However, they still found an increase in permeability in yellow poplar as growth rate increased. They concluded that other factors may also be involved in the increase in longitudinal sapwood permeability. These factors might include VLD and the type of perforation plates between vessel elements. Doungpet (2005) reported correlation coefficient between growth rate and VLA%, vessel frequency (VF), and VLD in six-year old *Populus deltoides* trees to be -0.137, -0.426, and 0.338 respectively. Therefore, an increase in growth rate may eventually result in more vessel diameter and consequently increases permeability values.

5. Conclusion

Current agroforestry practices (intercropping and initial spacing) may significantly influence the growth rate of trees rather than internal wood properties. In agroforestry systems, wider initial spacings are usually used to provide better sunlight for the agricultural crops. However, the wider spacings may have negative effects on the bole form of trees. In order to prevent this negative effect, narrower spacing may be used at the time of stand establishment; while the stand grows and crown of the trees expand, thinning and/or pruning may be used to provide enough sunlight for the agricultural crops. More growth rate induced by intercropping systems may influence wood properties. As to poplar-based

agroforestry systems intercropped with alfalfa in particular, this increase in growth rate should not necessarily end up in shorter fiber length in young poplar trees as was previously believed. In the meantime, intercropping with alfalfa and wider initial spacing may alter the capillary structure of poplar wood in a way that its permeability is increased leading to some improved technical acceptance of wood.

6. Acknowledgment

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Agroforestry for Biodiversity and Ecosystem Services - Science and Practice

Edited by Dr. Martin Kaonga

Agroforestry has great potential for reducing deforestation and forest degradation, providing rural livelihoods and habitats for species outside formally protected land, and alleviating resource-use pressure on conservation areas. However, widespread adoption of agroforestry innovations is still constrained by a myriad of factors including design features of candidate agroforestry innovations, perceived needs, policies, availability and distribution of factors of production, and perception of risks. Understanding the science, and factors that regulate the adoption, of agroforestry and how they impact the implementation of agroforestry is vitally important. Agroforestry for Biodiversity and Ecosystem Services: Science and Practice examines design features and management practices of some agroforestry practices and their impact on biodiversity and the ecosystem services it delivers. It also identifies policy issues for facilitating adoption of desirable agroforestry practices and gradual diminution of undesirable policies.

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