NIR-hyperspectral camera analyses for differencing agroforestry and forestry poplar woods

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Abstract Wood characteristics of trees grown in agroforestry systems are still little studied, while their growth conditions are different from conventional stands. This work focused on the impact of the agroforestry system on the lignin/cellulose ratio of hybrid poplar trees. One disk sample was harvested on 6 agroforestry (AF) and 6 forest control (FC) poplar trees, at breast height ground level (1.30 m). Every disk was analyzed by Near Infrared Hyperspectral imaging using a Specim FX17 (Specim, Spectral Imaging Ltd.). Images from hyperspectral camera analyses corresponding to absorbance spectra were collected at the wavelength of 1450 nm, attributed to first overtone O–H stretching vibration of lignin/extractives compounds, in order to clearly observe the chemical difference between AF and FC poplar woods. The results indicated significant difference between the chemical composition, based on estimated lignin content, of AF and FC poplar woods. According to the results from NIR-hyperspectral images analyses, the lignin content appeared to be lower in AF poplar wood (9.8 ± 1.1 pixels/mm^2) than in FC poplar wood (16.1 ± 3.8 pixels/mm^2). These results could be explained by the different tree growing conditions between the both systems. AF poplar tended to produce more tension wood and more

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juvenile wood than FC poplar, which resulted in a lower concentration in lignin.

Keywords Cellulose · Flexure wood · Growing conditions · Lignin · *Populus deltoïde* × *Populus nigra* · Koster · NIR-hyperspectral imaging

Introduction

Agroforestry is a dynamic, ecologically based natural resources management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels. Today's agroforestry draws from traditional practices but has been adapted to modern farming constraints: specific maintenance techniques, low tree density per hectare, trees aligned and chosen for their compatibility with crops (most often for food use) and their economic or environmental value.

Poplar is a fast-growing tree species that has been extensively planted in many countries and provides industrial wood for paper pulp, light packaging industry, plywood or even furniture or construction (Liesebach 2020). In addition to growing in plantations for wood production, poplar is also planted in agroforestry systems especially as a fast-growing windbreak and/or an extra income stream for farmers. Poplar tree is considered as a good choice for agroforestry systems due to (1) its little shading effect on crops; (2) its contribution to soil fertility through its leaf litter; (3) its suitability with a wide variety of commonly planted inter-crops as wheat, oat, sorghum, maize; (4) its wood production that could generate additional income at the end of the rotation (Chahal et al. 2012).

Indeed, due to its short rotation cycle, generally between 10 and 15 years, poplar provides a quick additional income for plantation owners, compared to other species. In addition, this rotation period can be reduced to 3–5 years for small diameter pulpwood for paper production, 6–8 years for medium diameter poplar, and 10–15 years for large diameter poplar for plywood production, depending on the stand plantation density, genotype and site conditions (Oliveira et al. 2020).

Thus, poplar is a local asset worth preserving and its timber has unique qualities such as resistance and lightness. Poplars (*Populus spp.*) has a rapid juvenile growth, resulting in a high volume production per hectare. Of course, the logs of the "high-value trees agroforestry system" are the most interesting for both veneer and sawmill processing, especially since these systems are becoming more prevalent.

Aboveground biomass in poplar plantations or forestry system (FS) and agroforestry systems (AF) has been widely studied around the world (Laureysens et al. 2004; Zabek and Prescott 2006; Fang et al. 2007; Christersson 2010; Fortier et al. 2010; Truax et al. 2012). These previous works reported that associating poplar trees and crops is more productive than crop rotations separating crops on one side and trees on the other side. For example, a traditional agroforestry plot, associating poplars with cereals, showed that a 100 ha agroforestry farm produces as much biomass as a 140 ha farm separating its crops (Dupraz and Liagre 2008). Intercrops production seems to be modified year by year by the increase of canopy cover, while wood production is mostly related to site conditions and tree density regulated by periodic thinnings (Etienne and Rapey 1999). Moreover, forestry systems with low planting density require more care and pruning of trees to achieve a high-value clean trunk (Nerlich et al. 2013). Based on growth data after 5–8 years under temperate and Mediterranean conditions, Báder et al. (2022) showed that widely spaced deciduous trees in agroforestry areas have grown very satisfactorily compared to the same species in adjacent forest stands. Van Noordwijk and Lusiana (1999) found that the height of the trees was always greater in the classical forestry timber system compared to the agroforestry system because dense planting of trees underwent competition between trees. Usually, forestry trees are more slender than agroforestry trees. They invest less resources in canopy development and more resources for trunk growth. At the opposite, agroforestry trees seem to develop larger crowns (compared to planted forestry trees). They produce more assimilates and since they are generally more exposed to the wind, the produce a larger trunk diameter, which provides the stem resistance. In other words, agroforestry trees are less slender than planted or control forest systems (Bonnesoeur et al. 2016). These differences could be explain by a difference in wood maturity (part of juvenile wood).

In spite of impacts of forestry conditions on tree growing and on woody biomass production, very little research has evaluated the quality of wood material coming from agroforestry systems and compared it to forestry systems. Moreover, the few results obtained in the literature are often in contrast to each other. Taghiyari and Sisi (2012) reported that 8 years old *Populus deltoids,* intercropped with maize, had larger wood volume compared to the trees from forestry plantations. They stated that the trunk diameter of *Populus nigra* intercropped with alfalfa was greater than in forestry plantations and the greatest difference in diameter growth occurred from age 3 to about age 7. Peszlen (1993) found that wood properties of poplars had no significant relationship with growth rate. In France, poplars (cultivar I-214) were found to have a nearly cylindrical shape in both agroforestry and forestry plantation systems. Through this study, Peszlen (1993) highlighted that the wood density, microbril angle and modulus of elasticity were reported very close in agroforestry and forestry trees. Thus, the wood quality of poplar from agroforestry was found to be very similar to wood quality produced in a forest (Kouakou et al. 2016). However, some researches have also emphasized that low stand density, pruning and a higher exposition to the wind within agroforestry systems could highly affect the tree growing kinetic, the wood anatomy and chemical composition, and finally the wood properties (Zobel and Van Buijtenen 1989; Uner et al. 2009; Novaes et al. 2010; Rocha et al. 2016).

NIR spectroscopy is also widely used in wood characterization, mostly to assess material properties based on chemical information (Leblon et al. 2013). The benefits of such a method reside in the lower time-consuming, labor-intensive, expensive and destructive conventional wet chemical analytical methods (Defoirdt et al. 2017). The NIR (Near-InfraRed) spectroscopy has been efficiently used for the assessment of chemical properties wood (Terrasse et al. 2021). Schimleck et al. (2003) showed that it is possible to accurately calibrate NIR models for a wide range of species that represent different taxa, wood chemistry and physical properties. More recently, high-resolution near-infrared hyperspectral image acquisition, resulting in an infrared spectrum for each pixel of the image, has been developed. Defoirdt et al. (2017) highlighted the usability of NIR hyperspectral imagery as proxy for density and lignin content of poplar wood, where NIR spectra were used for 2D tension wood and lignin mapping. In addition, this technic has been showed as a valuable tool to estimate the difference in lignin content between agroforestry and forestry walnut tree (Heim et al. 2022).This study aims to improve the knowledge about the chemical composition, especially based on the lignin content of poplar wood formed in agroforestry context (AF) poplar trees and compared to standard forestry control plots (FC). All samples were analyzed by NIR-spectroscopy hyperspectral camera, in order to evaluate the impact of the two silvicultural practices.

Materials and methods

Experimental site

The experiment was carried out in Lent, located in east-middle France (46°05′11.1"N 5°10′22.7"E and elevation 255 m). Two plots composed by 19 years old poplar and 13 years old, respectively in forest control and agroforestry plots, are studied. The poplar cultivar was “Koster” (*Populus deltoïde x Populus nigra*), showing a great adaptability in the whole France area (Paillassa 2002). Koster cultivar is supposed to be a good candidate for agroforestry systems: it shows a low sensibility to the wind, a good resistance against pruning, low water requirements and good adaptation to stations located outside the valley (Paillassa 2002; CRPF 2016). In our systems, the tree stand densities were around 50 trees/ha and 200 trees/ha in AgroForestry plot (AF) and Forestry Control (FC) plot, respectively (Fig. 1a). The planting lines of poplar trees were all Northwest–Southwest oriented, within the both plots (Fig. 1a).

Trees were spaced by 5×5 m in FC plot and 10×20 m in AF plot (10 m within the planting line, 20 m between each planting line) (Fig. 1b). In agroforestry system, fodder grass were annually harvested between each line on a 20 m wide strip for animal feedings. Both plots were exposed to a dominant wind coming from the Northwest direction (Fig. 1c).

Trees selection

As shown in Fig. 1a, 12 ‘Koster’ poplar trees were selected in the two AF (6 trees) and FC (6 trees) plots. All of the selected poplar trees (AF and FC) were harvested in April 2022, limiting the seasonal impact on wood chemical composition (i.e., starch

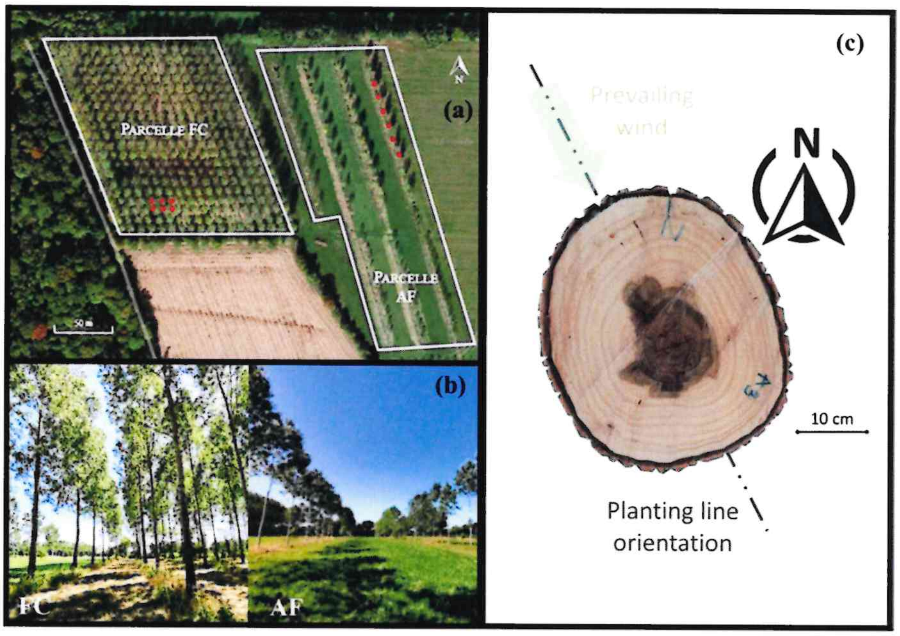


Fig. 1 **a** Poplar trees selection (red bullets) in the agroforestry (AF) and forestry control (FC) plots, in Lent located in east-middle France southern France. **b** Pictures of poplar trees distribution in AF and FC plots. Schematic view of tree position according to the prevailing wind (North-Northwest) direction and the planting line orientation (from Northwest to Southwest)

in sapwood). For each plot, the 6 trees were selected mainly according to constraints related the owner of the plots. However, FC trees were harvested at locations in the plot so that the wind effect would be representative of the entire stand (Fig. 1a). In addition, even if AF trees were collected at the periphery, these are exposed to the wind as the other trees from the plot because of the wide spacing between trees and planting line. The poplar trees issued from AF plot was marked with references from A3 to F3, and the poplar trees coming from FC plots were refereed from G3 to L3.

Sampling

For each poplar tree, a 5 cm thick wooden disc was collected at 1.30 m from the ground. Each disc was lightly sanded in order to get a surface without irregularities limiting high variability in scattering effect during NIR-S measurements (Mancini et al. 2019). The machined face was then vacuum cleaned to avoid the accumulation of wood powder in the wood cells, which could impact the NIR-S measurements. Finally, the discs samples were cut in two equal parts, along the north–south direction, in order to obtain samples with a size adapted to the capacity of the hyperspectral camera device (max: 20×40 cm). All the samples were placed in a conditioning chamber (regulated at 20 ± 2 °C, 65 ± 5% Relative Humidity). NIR-Hyperspectral analysis were performed after mass stabilization. The process of wood sampling and preparation is illustrated in Fig. 2.

NIR-hyperspectral camera analyses

AgroForestry versus forestry wood discs

Hyperspectral measurements were performed on the half-wooden discs using a Specim FX17 camera (Specim, Spectral Imaging Ltd.). The distance between the objective of the camera and the surface of the wood samples was fixed at 22 cm. The settings were a spectral range of 933–1721 nm and a 3.5 nm increments. Each NIR spectrum was digitized in 224 wavelengths. The spatial resolution was set to 0.27 mm/pixel. For each image, spectral data were collected as a 3D matrix of $640\times1002\times224$ values. The dimensions 640×1002 were associated with the spatial dimensions of each disc. Images from hyperspectral camera analyses corresponding to absorbance spectra were collected at the wavelength of 1450 nm, attributed to first overtone O–H stretching vibration of lignin/extractives compounds. The both half-wooden discs images from the same tree were merged together. Then, these images were analyzed with Image J 1.53 k software (Rasband 2018) in order

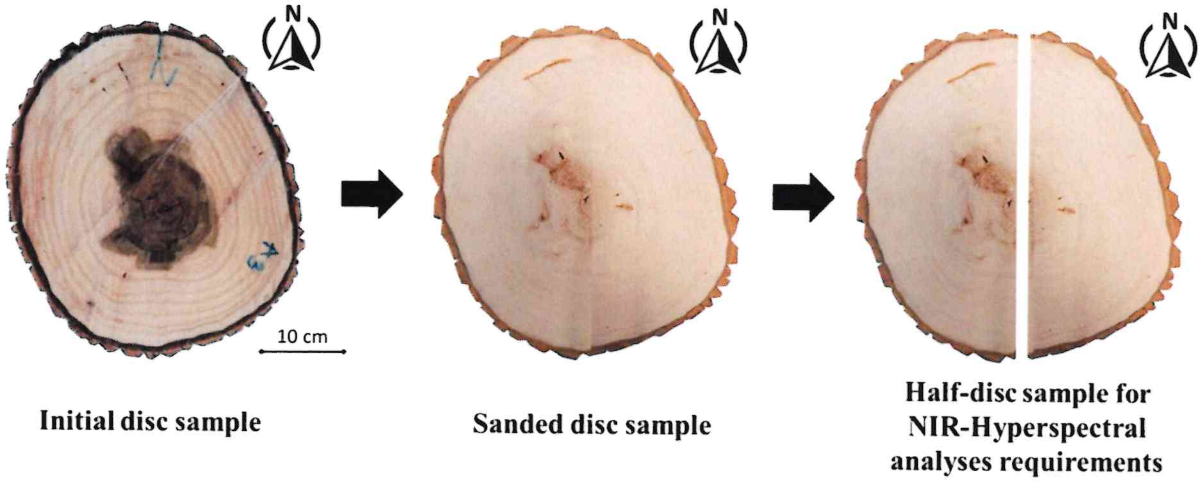


Fig. 2 Process of wood sampling and preparation for NIR-hyperspectral camera analyses

to determine the values of pixels for each color in the RGB referential. The values of RGB pixels were analyzed on each AF and FC poplar wooden disc without taking the bark into consideration (Fig. 3).

Flexure woods from agro forestry and forestry poplar trees

Similar image analyzes were performed on selected areas, representative of Tensile Flexure Wood (TFW) and Compression Flexure Wood (CFW). The TFW and CFW were studied by Roignant et al. (201), and they are represented in Fig. 4. These two areas were analyzed for all AF and FC poplar discs, according to the same protocol previously described. The values of RGB pixels were then analyzed on each flexural wood and opposite wood areas. The bark portion was removed from the analyses (Fig. 4).

Results and discussions

Figure 5 shows the raw and average NIRS spectra of wood samples from poplar trees from FC and AF samples. Table 1 indicates the NIRS absorption bands associated with the main chemical components contained in the wood specimens. It is clear that the differences in chemical composition between AF and FC poplar wood depend mainly on differences in the content of celluloses (peak 7) and on the amount of

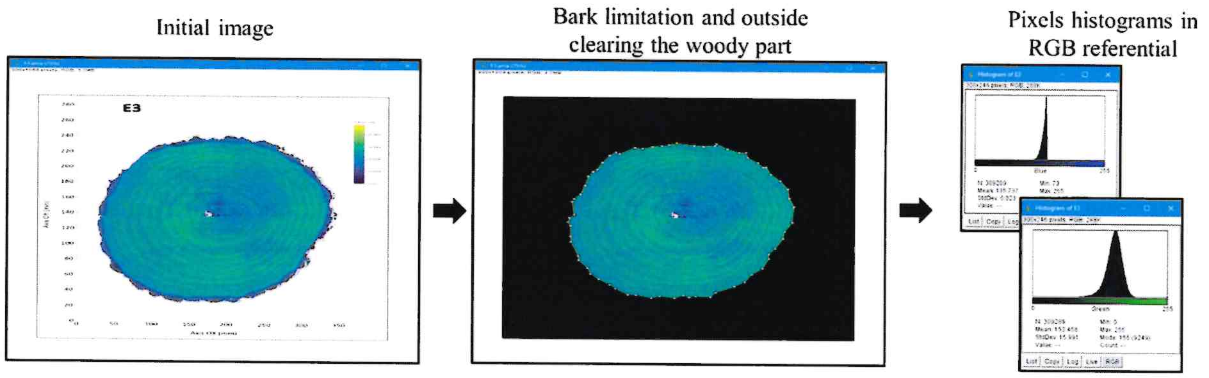
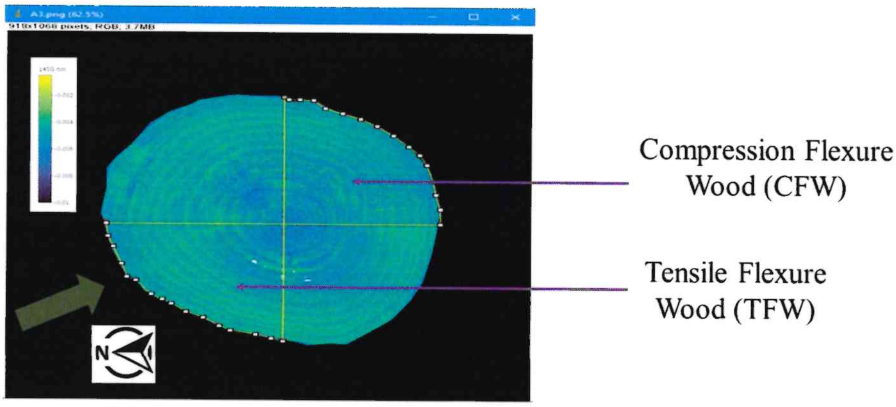


Fig. 3 Process analyze concerning determination of RGB pixels on the images from hyperspectral camera (E3 for example), using Image J 1.53 k software

Fig. 4 Selection of Tensile Flexure Wood (TFW) and Compression Flexure Wood (CFW) areas for the determination of RGB pixels on the images from hyperspectral camera (A3 for example), using Image J 1.53 k software. The green arrow represents the direction of daily wind



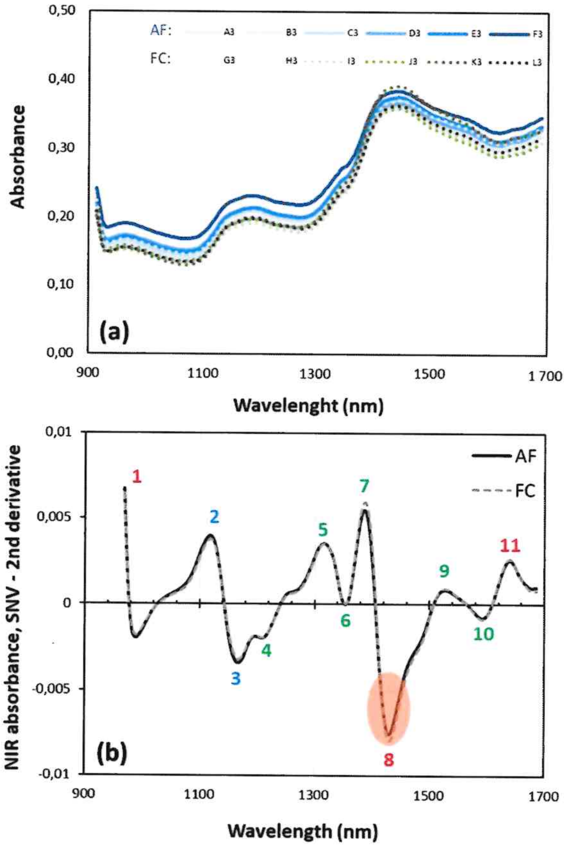


Fig. 5 **a** Raw absorbance spectra and **b** average absorbance spectra after pretreatments (SNV correction—2nd derivative) of AF and FC poplar trees. The area in orange specifies the wavenumber used for the NIR-hyperspectral camera analyses. Peaks 5 and 6 refer to the hemicellulose. Peaks 4, 7, 9 and 10 refer to the cellulose. Peaks 2 and 3 and peak area delimited around peak 8 refer to lignin. Peaks 1 et 11 refer to extractives

lignin/extractives (peak 8). The highest difference between AF an FC poplar sample was observable for a wavelength of 1450 nm that is identified by peak number 8 in Fig. 5.

Images from hyperspectral camera analyses, presented on Fig. 6, show the absorbance spectra collected at the wavelength of 1450 nm (most discriminant wavelength between FC and AF), which is attributed to first overtone O–H stretching vibration of lignin/extractives compounds. The hyperspectral images associated to their respective blue and green color intensities, presented in Fig. 6, clearly highlight that AF discs samples contained less lignin/extractives components (low intensity in blue color) than those of FC samples.

In addition, Table 2 presented the average value and the associated standard deviation of the maximal value of the number of green and blue pixels, observed on FA and FC samples. These results show that the AF discs samples have a maximal value of the number of blue pixels /mm^2 of 9.8 ± 1.1, whereas the AF discs samples have a maximal value of the number of green pixels /mm^2 of 16.1 ± 3.8, showing that AF poplar contains lower lignin/extractives content (low number of blue pixels) than those of FC samples. Moreover, previous work conducted on AF and FC hybrid walnut (*Juglans regia* × *nigra*) trees shown that the extractives fraction is not sufficient to explain the chemical differences between AF and FC trees and to classify these trees according to the silvicultural system (Heim et al. 2022). Moreover, poplar wood is well known to have a low extractives contents, so the chemical difference between AF and FC poplar is probably mainly due to their lignin contents. These differences in macromolecules

Table 1 NIRS absorption bands associated with the main wood components (cellulose, hemicelluloses, lignin and extractives) contained in the poplar wood specimens

Index	Wavelength bands (nm)	Bond vibration	Structure	Remarks	References
1	900–980		Lignin / Extractives	The major vibrations include the yellow–brown color of the wood that are primarily due to the presence of lignin and extractives	Kelley et al. (2004) Yi et al. (2017)
2	1100–1150	Second overtone C-H stretching of CH_3 groups	Lignin	CH_3 groups and aromatic moieties	Workman & Weyer (2007) Schwanninger et al. (2011)
3	1150–1200	Second overtone asym. C-H, HC=CH stretchings	Lignin	–	Kelley et al. (2004) Schwanninger et al. (2011)
4	1200–1220	Second overtone C-H stretching	Cellulose	Two to three bands t.a. CH and CH_2 groups, cellulose	Schwanninger et al. (2011)
5	1290–1310	First overtone C-H stretching + C-H deformation	Hemicelluloses / all	Tentative assignment to CH_3 groups in acetyl ester groups in hemicelluloses and lignin and all wood components after acetylation	Schwanninger et al. (2011)
6	1310–1350	First overtone C-H stretching and C-H deformation	Hemicelluloses / all	Tentative assignment to CH_3 groups in acetyl ester groups in hemicelluloses (normal wood) and all wood components after acetylation	Schwanninger et al. (2011)
7	1350–1380	First overtone O–H stretching	Cellulose	Amorphous regions in cellulose	Fujimoto et al. (2007)
8	1420–1460	First overtone O–H stretching	Lignin / Extractives	Vibration of phenolic hydroxyl groups	Schwanninger et al. (2011)
9	1570–1600	First overtone O–H stretching	Cellulose	Crystalline region of cellulose in C_1 and C_2	Tsuchikawa and Siesler (2003) Schwanninger et al. (2011)
10	1600—1610	First overtone O–H stretching	Cellulose	Strongly H-bonded O–H group in cellulose,	Schwanninger et al. (2011)
11	1610–1650	First overtone C-H stretching	Extractives	–	Schwanninger et al. (2011)

Index numbers (in color) relate to the specific band in Fig. 4b

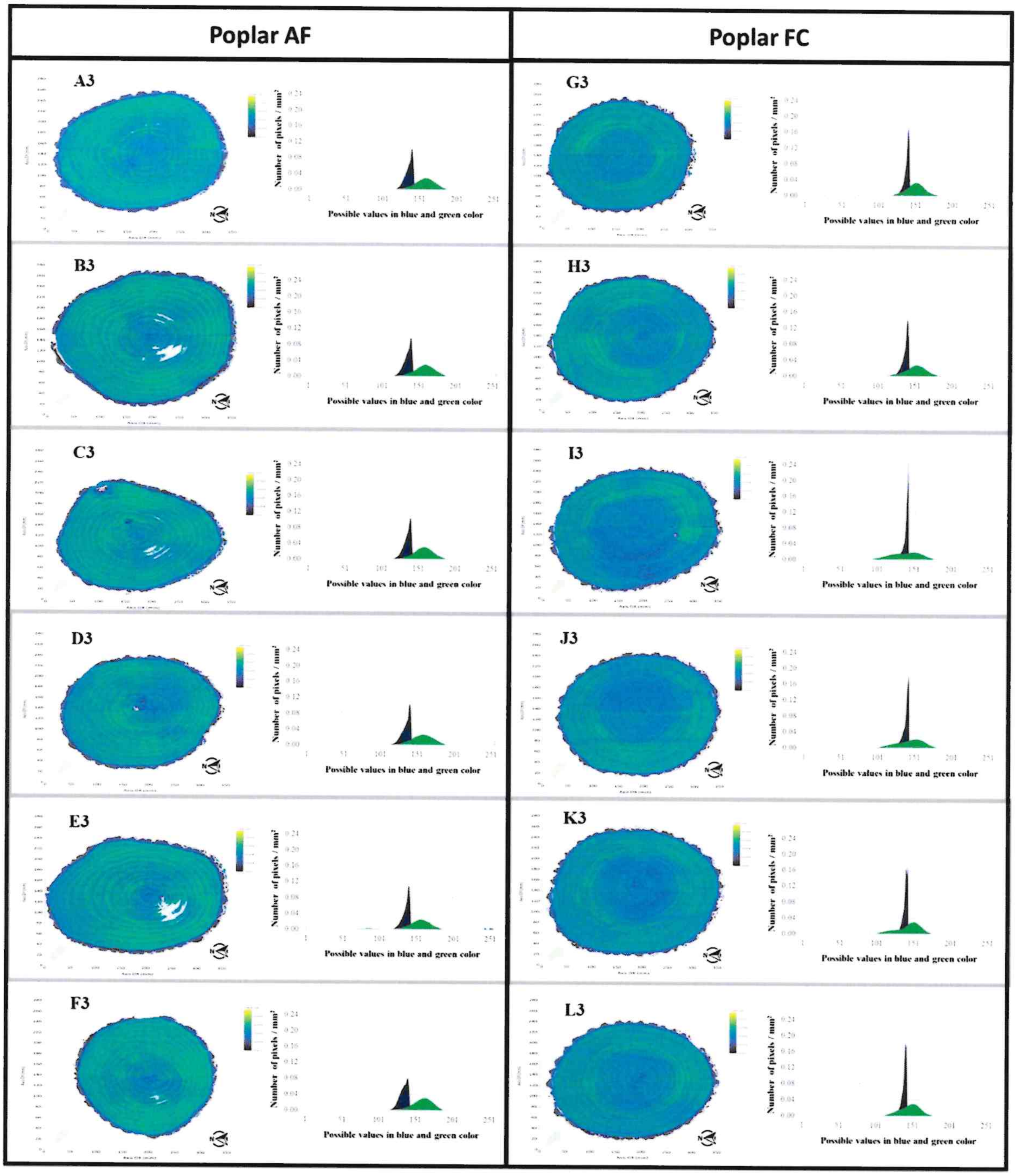


Fig. 6 Illustrations of NIR absorbance after pretreatment (SNV correction—2nd derivative) measured for the wavelength of 1450 nm. These images were acquired from agroforestry (AF) and forestry control (FC) slices of air-dried wooden discs. Images were associated to their histograms of pixels values in blue and grey color (based on RGB referential). On the left, the color scale ranges from yellow to dark blue and represents the intensity of NIR absorbance at the wavelength of 1450 nm, which is attributed to first overtone O–H stretching vibration of lignin/extractives compounds (Table 1). On the right, the histograms were constructed from the analyses of the wooden disc pictures recorded by hyperspectral camera. The blue pixels represent the lignin/extractives contents. The green arrow represents the main direction of wind

Table 2 Maximum value [and associated standard deviation (SD)] of the numbers of green and blue pixels, observed on the images form AF and FC poplar discs, obtained by NIR hyperspectral Imagery at the wavelength of 1450 nm

Numbers of pixels /mm^2				
Pixels colors	AF		FC	
	Maximum value	SD	Maximum value	SD
Blue	9.8	±1.1	16.1	±3.8
Green	2.8	±0.2	2.7	±0.5

chemical composition could be explain by the stand density. Jiang et al. (2007) highlighted that poplar tree growing in a stand with low planting density presented higher proportion of juvenile wood basal area at breast height, with higher fiber length, than those from plot with high stand density. The juvenile wood of poplar usually contains higher content of hollocelluloses than in mature wood (Bao et al. 2001). An inverse correlation was found concerning the lignin fraction (Bao et al. 2001). However, these statements need to be taken with precaution because the AF poplar are three years younger than FC poplar tree, which gives them probably more juvenile wood in relative value.

The results obtained by analyses carried out on tensile flexure wood (TFW) and compression wood (CFW) enlighten that TFW contains lower lignin content than CFW for Agroforestry poplar tree (Fig. 7). The same results were observed for trees growing in forestry system.

The higher exposition toward dominant wind present within agroforestry plot could also affect the wood chemical composition of trees growing in such system compare to those from traditional forest area. Due to the higher wind exposure, poplar trend to produce flexure wood during its growing. This flexure wood was first defined by Telewski (1989) as the result of the regular mechanical deformations of the stem. In case of poplar, its anatomy was carefully analyzed by Roignant et al (2017) who enlightened several similarities between tension wood and flexure wood formed in the stretched zone, called Tensile Flexure Wood. Especially, it can contain a gelatinous G layer in the stretched cells. In many tree species including *Populus*, tension wood fibers form a distinctive gelatinous inner wall (GL). This G layer is then thick and is known to have a high cellulose content (Côté et al.1969; Mellerowicz and Sundberg 2008) and a microfibril angle close to zero, i.e. aligned to the cell axis (Prohdan et al. 1995), no lignin (Pilate et al. 2004), and a high mesoporosity (Chang et al. 2009). Our hyperspectral images (Figs. 6 and 7) showed larger areas of tensile flexure wood (green arrow) in all AF samples than in FC samples. Roignant et al. (2017) highlighted that tensile flexure wood is characterized by lower vessel density, higher fiber diameter, thicker S layer, and the presence of G layer but no difference in lignin content; while Pilate et al. (2004) showed also lower lignin content in tension wood of poplar. These statements are in agreement with the results obtained with AF poplar trees.

In addition, Fang et al. (2008) showed that the growing strength intensity (GSI), that is a good indicator of relative longitudinal growth stress magnitude within trees of the same species, affects the chemical composition of poplar wood. The higher the GSI values, the higher the cellulose content of the wood. Opposite trends for lignin and hemicelluloses contents were also observed in this previous study (Fang et al. 2008). With results support our findings concerning the lower amount of lignin content in tension wood compared to those of opposite wood in AF poplar, that are more submitted to wind than FC trees, whereas no difference were observed on FC Poplar.

However, the literature states sometimes that juvenile wood is slightly richer or similar in lignin than in cellulose (Morais et al. 2017; Lu et al. 2021). This would suggest that the effect of flexure wood is dominant over the presence of juvenile wood in the chemical composition comparison between AF and FC poplar trees.

Even if the FC poplars were three years older than the AF poplars, this age differential does not seem to be a parameter that could explain such a difference in chemical composition of these two samples batches. In other words, three years of age difference between AF and FC trees on the average of all the measurements carried out does not seem to be affecting to alter the observed trend. In fact, Krutul et al. (2019) compared several poplar clones and enlightened that their cellulose content did not depend from the species of tree age. Moreover, the lignin content increased slightly as a tree age, but its content

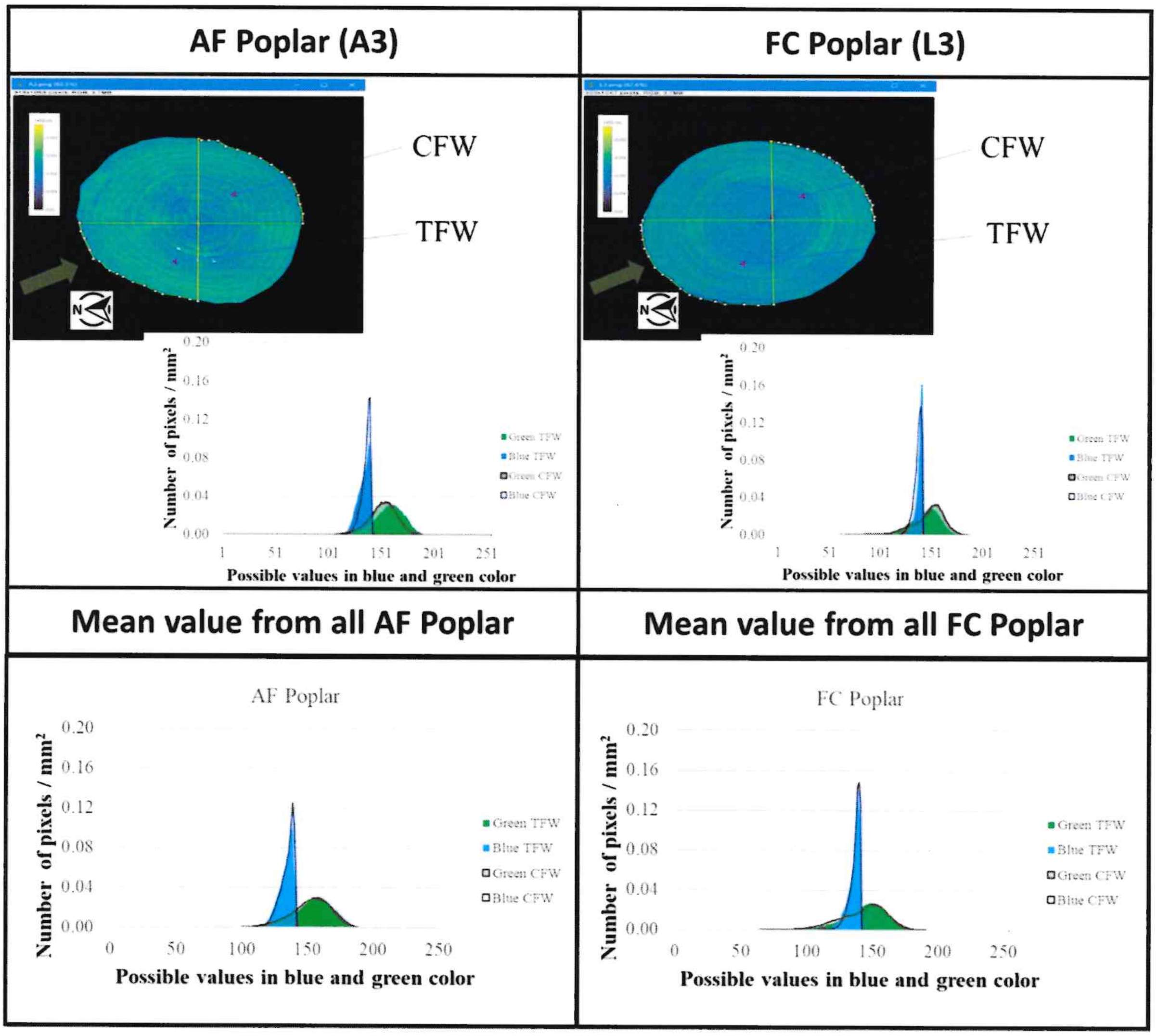


Fig. 7 Focus on Tensile Flexure Wood (TFW) and Compression Flexure Wood (CFW) wood areas from agroforestry (AF) and forestry control (FC). NIRS Images were associated to their histograms of pixels values in blue and grey color (based on RGB referential). On the left, the color scale ranges from yellow to dark blue and represents the intensity of NIR absorbance at the wavelength of 1450 nm, which is attributed to first overtone O–H stretching vibration of lignin/extractives compounds (Table 1). On the right, the histograms were constructed from the analyses of the wooden disc pictures recorded by hyperspectral camera. The blue pixels represent the lignin/extractives contents. The green arrow represents the main direction of wind

in 7-year-old wood was already similar to the level found in 30 years-old wood (Krutul et al. 2019).

Conclusions

The hyperspectral methods, which used a camera, was quick and easy to use. It provided results with a new angle to understand the wood chemical composition of poplar trees allowing assessing the wood quality when trees grow under different growing conditions. In this article, hyperspectral NIR imaging was used to analyze the quantitative distribution of lignin content in agroforestry and forestry poplar trees.

The use of the method for agroforestry systems allowed enlightening differences of chemical components between forestry poplars and poplar woods formed in agroforestry systems; which are still very under-studied by now. Hyperspectral imaging highlighted that AF poplar samples contained lower lignin/extractives compounds than FC samples. In addition, higher proportion in lignin content in the tensile flexure wood in comparison to the compression flexure wood were observed from all AF samples than those from FC samples. This suggests that AF poplar samples contain more cellulose than FC poplar trees. This is a typical pattern of trees that daily experience windy environments and who produce flexure wood in order to keep their straightness and verticality. However, the literature states sometimes that juvenile wood is slightly richer or similar in lignin than in cellulose, suggesting that the effect of flexure wood is dominant over the presence of juvenile wood in the chemical composition comparison between AF and FC poplar trees. In this sense, it could de be interesting to carried out, in the near future, micro-density and micro-fibril angle (MFA) analyses do determine the proportion of juvenile wood from AF and FC poplar trees.

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Declarations

Competing interests The authors declare no competing interests.

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