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RESEARCH ARTICLE

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Rapid discrimination of wood species from native forest and plantations using near infrared spectroscopy

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Abstract

Aim of study: To verify how well near infrared (NIR) spectroscopy is able to discriminate wood specimens from natural and planted forests. This study was carried out using tropical trees from Brazil.

Area of study: Wood specimens coming from Lavras (21°10′S, 44°54′W), Paraopeba (19°16′S, 44°24′W) and Belo Oriente (19°17′S, 42°23′W) cities, Minas Gerais state, southeastern Brazil were insvetigated.

Material and methods: NIR spectra were recorded in the radial surface of wood specimens of four native species (*Cedrela* sp., *Apuleia* sp., *Aspidosperma* sp. and *Jacaranda* sp.) and two commercial clones (*Eucalyptus* for bioenergy and pulp & paper).

Main results: The principal component analysis (PCA) of spectral information revealed that it is possible to distinguish wood from planted and native forests. The dispersion of scores in the graphic formed by the first and second principal component formed two groups allowing differentiating very clearly the Eucalyptus clones from the native woods. The partial least squares discriminant analysis (PLS-DA) allowed the prediction of group of species with a high degree of correct classification. The PLS-DA models performed from untreated NIR spectra obtained 86 to 100% accuracy for the natural wood species.

Research highlights: From PLS-DA of treated NIR spectra, no *Eucalyptus* wood sample was classified as a natural forest species and vice versa. NIR technique associated with multivariate statistics are promising to discriminate wood specimens from native or planted forests and thus identify frauds.

Additional keywords: illegal logging; forest exploitation; wood identification; timber classification.

Abbreviations used: 1d (First Derivative); NIR (Near Infrared); PCA (Principal Component Analyses); PLS-DA (Partial Least Squares Discriminant Analyses); PLS-R (Partial Least Squares Regression); RER (Range Error Ratie); RMSE (Root Mean Square Error); RPD (Ratio of Performance to Deviation); SNV (Standard Normal Variate).

Authors´ contributions: FMGR: Elaboration of the manuscript, statistical analysis and acquisition of the spectra. JMA: Acquisition of spectra. PRGH: Coordination of the research project, preparation of the manuscript and statistical analysis. All authors read and approved the final manuscript.

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Introduction

Deforestation and illegal logging in natural forests are a global concern because of the threats they pose to the rich biodiversity of some regions and because of their contributions towards climate change (Brito & Barreto, 2006). In Brazil, despite the enforcement against illegal logging has improved, the deforestation is still increasing. One of the great challenges is to identify illegal from legal wood. According to Yang *et al.* (2015) the traditional methods for wood identification are time consuming, laborious and require expertise because it involves physical, anatomical, and visual aspects of wood species.

Discriminate natural and planted forests is to perceive differences between them and to classify them in function of these differences. The non-destructive and fast separation of wood species could improve the control in terms of monitoring of forest exploitation and wood transportation. Near infrared (NIR) spectroscopy has been successfully used for the nondestructive measurement of organic materials such as agricultural products or foods (Tsuchikawa, 2007). NIR spectroscopy with aid of multivariate statistics and computational systems is useful not only for quantitative but also for qualitative applications, including classification of wood materials (Tsuchikawa & Kobori, 2015).

Many studies have shown that it is feasible to identify wood species by NIR spectroscopy coupled with multivariate analysis proposing a new method to rapidly identify or classify wood samples. Promising classifications based on NIR spectra recorded fromdifferent wood samples of the same genera were reported in literature for *Eucalyptus* (Michell & Schimleck, 1998), *Pinus* (Espinoza *et al.*, 2012), *Larix* (Gierlinger *et al.*, 2004) and *Quercus* (Adedipe *et al.*, 2008). In *Eucalyptus*, Schimleck *et al.* (1996) recorded NIR spectra from wood meals and discriminated woods samples by PCA (Principal Component Analyses), showing that it was possible to differentiate wood from different *Eucalyptus* species (*E. globulus, E. grandis* and *E. nitens*) and provenances (Victoria and Tasmania), and woods samples from the same species of *Eucalyptus* on different sites. Few studies presented models for classification of wood from different genera. For instance, Brunner *et al.* (1996) classified twelve different species of wood according to their NIR spectra suggesting that NIR would be able to distinguish wood samples of the same species but from different origins. Russ *et al.* (2009) have successfully classified seven hardwood species by PCA calculated from their NIR spectra recorded from wet and dried chips. Yang *et al.* (2012) applied the technique in eight rosewood samples and clearly classified them in eight categories using three-dimensional PCA scores plot. These studies have shown promising findings in regard to the ability of NIR spectroscopy associated with multivariate analysis for classifying wood samples.

This approach could be useful in situations where wood species are visually and anatomically similar and can be improperly commercialized. In regard to this issue, Pastore *et al.* (2011) have investigated four native rainfall forest tree species by NIR spectroscopy. They reported interesting classifications for four native species and showed that it is possible to perform safe discriminations of *Swietenia* (mahogany), *Carapa* (andiroba or crabwood), *Cedrela* (cedar) and *Micropholis* (Curupixá) woods with a very low probability of misclassifying a sample. Cooper *et al.* (2011) used the same approach for differentiating certain wood species groups. They successfully distinguished true firs (balsam fir (*Abies balsamea* (L.) Mill.) and sub alpine fir (*Abies lasiocarpa* (Hook.) Nutt.)) from pine and spruce in eastern and western spruce-pine-fir, respectively. Yang *et al.* (2015) also applied the same approach and successfully discriminated three wood genera (*Pometia, Instia* and *Couratari*) from Beijing wood market.

Here, wood species from native forest and commercial plantations were investigated in order to verify how well NIR spectroscopy is able to discriminate wood specimens from natural and planted forests. This technology would be useful as a tool to be used by control agents for supervising and monitoring illegal logging and deforestation.

Material and methods

Biological material and specimens preparation

Wood specimens from natural forest (cerrado biome) and commercial plantations typically found in Brazil were used in this study. The wood specimens from natural forests belongs to the following genera: *Cedrela* sp. (Cedar, C), *Apuleia* sp. (Garapa, T), *Aspidosperma* sp. (Peroba, P) and *Jacaranda* sp. (Rosewood, J). The natural forest is located at Lavras municipality, Minas Gerais state, southeastern Brazil (21°10′S, 44°54′W).

On the other hand, *Eucalyptus* wood represented the planted forests, the main genera cultivated for industrial application in Brazil. In order to represent the large variability in terms of genetic material used in reforestation in Brazil, *Eucalyptus* clones commercially used by two forestry companies were selected: i) Vallourec (V&M do Brasil) that utilizes hybrids of *Eucalyptus grandis* × *E. urophylla* at 6.5 years old located at Paraopeba city (19°16′S, 44°24′W) with focus on charcoal for bioenergy purposes and ii) Cenibra Nipo Brasileira S.A. that utilizes hybrids of *Eucalyptus grandis* × *E. urophylla* at 6 years old located at Belo Oriente (19°17′S, 42°23′W) state of Minas Gerais, Brazil, for cellulosic pulp production.

The total wood sampling was composed by six vegetal materials: 4 genera from native forest and 2 different types of *Eucalyptus*. The wood specimens used in this study came from the same experiment described in Ramalho *et al.* (2017) who investigated the charcoal produced from these wood specimens.

Ninety wood specimens with nominal dimensions of 35 mm × 35 mm × 100 mm (R × T × L) were removed from the first log of felled trees of each vegetable material, except for *Cedrela, Aspidosperma* and *Apuleia* genera that was represented by 45, 88 and 87 specimens, respectively. The total sampling was composed by 490 clear specimens [(90 · 3) + 45 + 88 + 87)] free of defects and well defined tangential-longitudinal and radial-longitudinal surfaces.

Specimens were conditioned in a room set for 20°C and 65% relative humidity to maintain the equilibrium moisture content (EMC) of ~14% prior to NIR spectra recordings.

NIR spectra acquisition

The near-infrared spectra were acquired using the Bruker spectrometer (model MPA, Bruker Optik GmbH, Ettlingen, Germany) based on a Fourrier transform and equipped with an integrating sphere. Spectral acquisition was performed within the 12,500 - 3,600 cm^{-1} with a spectral resolution of 8 cm^{-1} in diffuse reflection mode. Each spectrum represented the average of 32 scans. NIR spectra were recorded in the center of the two sides of the longitudinal-radial surfaces of each wood samples and averaged. Previous papers have indicated that the radial surface is more suitable for recording NIR spectra because is more representative (*e.g.* Hein *et al.*, 2009; Costa *et al.*, 2018). First derivatives (13-point filter and a second order polynomial) using the Savitzky & Golay (1964) algorithm and Standard Normal Variate (SNV) transformations were applied on the NIR spectra to enhance the quality of the information and analyses.

Multivariate statistical analysis

PCA were calculated for compressing the main information in a set of variables into a lower number of new variables by means of the Chemoface (Nunes *et al.*, 2012, v. 1.61, http://ufla.br/chemoface/) software. The PCA were calculated using full model size and maximum of eight principal components. For cross-validations 8 segments of 60 samples per segment were adopted while for test set validation were done using 2/3 of samples in calibration set and the remaining 1/3 in test set. Martens' uncertainty test (Westad & Martens, 2000) was used to select the wavenumbers with significant x-loadings. Outliers were identified from the analyses of residuals x-variances and leverage value plot. The number of latent variables (LVs) adopted for each model corresponded to the first minimal residual x-variance.

Partial least squares discriminant analyses (PLS-DA) were carried out for developing models for classifying wood species. The PLS-DA classification method, which is based on the PLS-R (partial least squares regression) approach, correlated two blocks of variables, X (independent variables) and Y (dependent variables). The independent variables (X) were the NIR spectra matrix while the dependent variables (Y) were the classes of wood species. For evaluating PLS-R regressions, the root mean square error (RMSE), ratio of performance to deviation (RPD) and range error ratio (RER) were used. As described in Costa *et al.* (2018), the RMSE measures the efficiency of the calibration model to predict the property of interest in many unknown sample, while the RPD is a way to identify the accuracy of the calibration and is the ratio between the standard deviation of the reference values and RMSE. The RER is the ratio between range of reference data and standard error of prediction. According the AACC (1999) any model that has a RER $\geq$ 4 is qualified for screening calibration. When RER $\geq$ 10 the model is acceptable for quality control, and if RER $\geq$ 15 the model is very good for research quantification.

The samples were grouped in six different classes: EC (*Eucalyptus* clones commercially used by Cenibra Nipo Brasileira S.A.), EV (*Eucalyptus* clones commercially used by Vallourec do Brasil), C (*Cedrela* sp. from natural forest), J (*Jacaranda* sp. from natural forest), P (*Aspidosperma* sp. from natural forest) and T (*Apuleia* sp. from natural forest). The classification of the wood specimens into classes of vegetal material was carried out through PLS-DA and the percentages of correct predictions were analyzed. The PLS-DA models were validated using cross- and test set validation methods. The cross-validation was carried out using eight segments while for the independent test set validation 2/3 of the samples were used in calibration set and 1/3 in validation set.

Results

NIR spectral signatures recorded from wood of natural forest and commercial plantations are shown in Fig. 1. Each NIR spectrum represents the average of NIR spectra taken from several wood specimens. In short, it is not possible to distinguish materials from their NIR signature because no interpretation can be properly done from such visual analysis (Fig. 1). Thus, multivariate statistical analysis was carried out for distinguishing vegetal material from their NIR spectra.

PCA were carried out from untreated and mathematically treated NIR spectra in order to reduce and concentrate the information in few principal components (PCs). Table 1 displays the cumulative explained variance taken into account for each PC. For instance, the first PC of the untreated NIR spectra is sufficient for explaining 98.08% of the variance between specimens. The scatter plot of the PC 1 and PC 2 from the PCA of the untreated NIR spectra is shown in Fig. 2A. Fig. 2B shows the first and second PC of the NIR-based scores after normalization (SNV) followed by first derivative of NIR spectra recorded from natural and planted wood specimens. From this analysis, two *Eucalyptus* types formed a clear group while wood

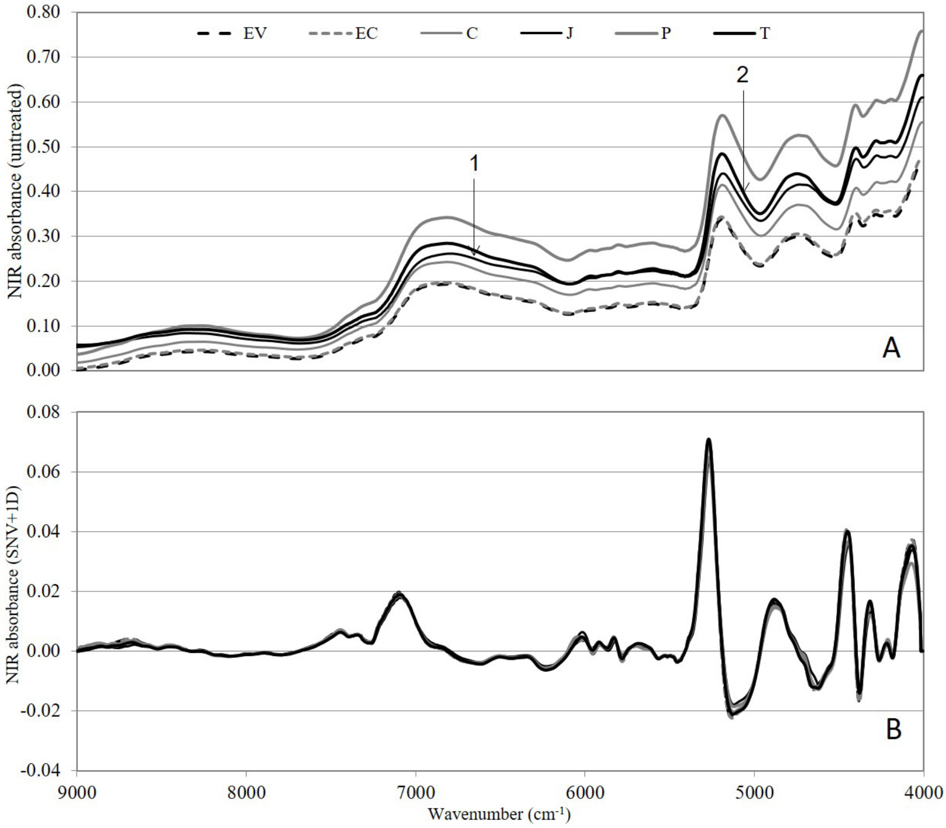

Figure 1. Original (A) and treated (B) NIR spectra recorded from wood of native forest trees (for abbreviations see text) and commercial plantations.

specimens from natural forests were graphically organized independently.

As in PCA approaches, PLS-DA were performed from treated NIR spectrum to verify is even better classifications could be achieved. The statistics associated to the preliminary PLS-R used in the following PLS-DA models are presented in Table 2, and the general graph of the regression coefficients is shown in Fig. 3. These preliminary PLS-R models developed for estimating continuous values in each of six categories (EC, EV, C, J, T, P) taking into account the reference data 1 (for specimen belonging to the correct category) and 0 (for specimen belonging to another category).

Table 1. Explained X-variance (in %) for each principal component by treatment applied in NIR spectra for discriminating wood from native and plantations tree species.

	Untreated	1d	SNV	SNV+1d
PC 1	98.08	69.28	70.38	63.113
PC 2	99.49	87.96	92.01	76.485
PC 3	99.75	91.28	96.41	85.116
PC 4	99.92	94.80	98.26	91.461
PC 5	99.95	95.94	98.73	94.104

1d: first derivative. SNV: standard normal variate.

The correct classifications of native species using the untreated spectra (for both cross-validation and test set) obtained values above 99%, except for the species named T (Table 3). Based on NIR spectra treated by SNV and first derivative (1d) method the PLS-DA yielded classification 100% corrects for all native species both for cross- and test set validation (Table 4).

Discussion

NIR spectra signature

Fig. 1 displays NIR spectra signatures taken from 9,000 to 4,000 cm^{-1} on the radial surface of wood specimens. According to Brereton (2003), this absorption bands correspond to the specific functional groups present in wood samples. Most band assignments for wood has been presented by Schwanninger *et al.* (2011), in which they described band locations in wavenumber, the component likely to absorb at this band location and also the bond vibration.

Here, after treatment of the spectra using standard normal variate and first derivative (SNV + 1d), the existence of the absorption bands became more evident at certain wavenumbers (Fig. 1B), although the peaks

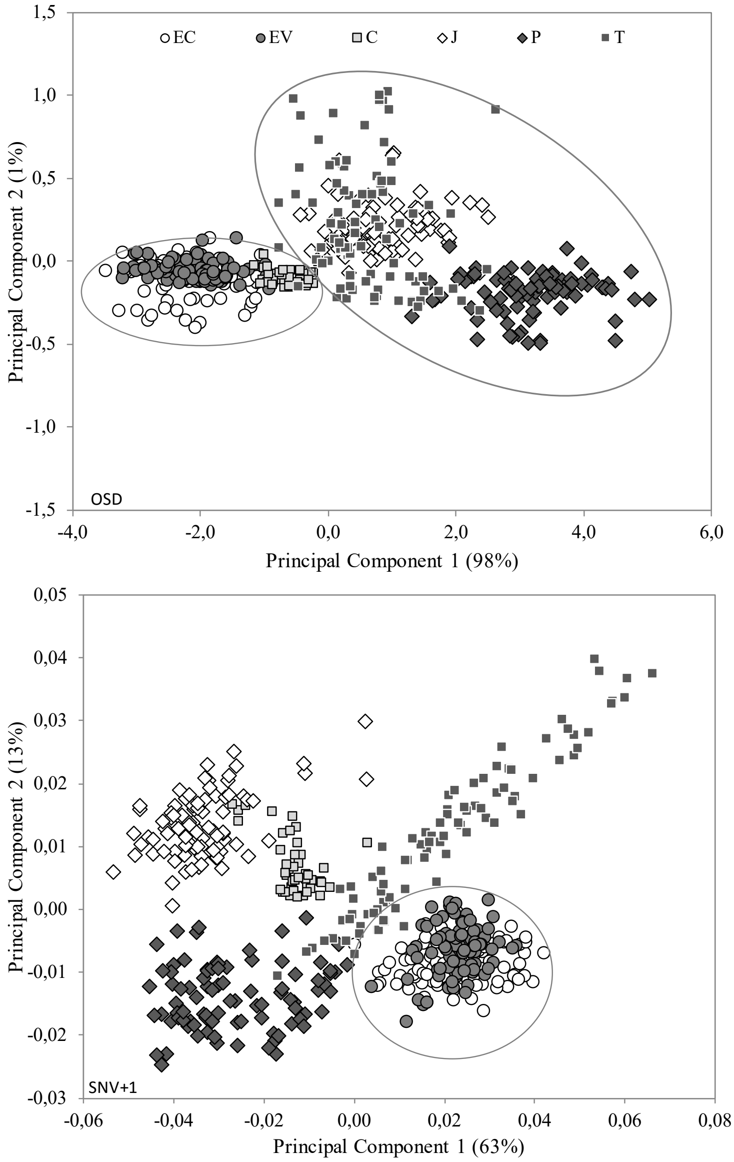

Figure 2. Two-dimensional scatter plot of the first and second PC of the PCA scores of untreated NIR spectra (Model OSD, original spectra data) (A) and after normalization (SNV) and first derivative (1d) of NIR spectra recorded from the surface of native and planted wood samples (Model SNV+1d) (B).

are inflection on raw spectra. From a visual analysis, small differences between NIR spectra of native woods can be observed in terms of intensity of the absorption bands at certain wavenumbers (indicated by narrows). For instance, line J (black fine line) decreases less intensely than lines T, P and C (native woods) in the zones indicates by the narrows. However, no difference can be detected between NIR spectra measured from *Eucalyptus* wood (dotted lines).

Principal component analyses (PCA)

An exploratory analysis using NIR spectroscopy is useful and important for wood science and industry as well as quantitative analysis (Tsuchikawa, 2007). PCA was performed with the treated and untreated spectra. The mathematical treatment did not improve the results in terms of increasing the explained variance (Table 1) but from a visual analysis of the score plots, treatment on NIR seems to clarify the separation of different types of wood.

It was possible to identify two wood groups with the PCA of the untreated NIR spectra (Fig. 2A). These clusters were formed because each vegetal material presents different characteristics and properties, such as the chemical composition and anatomical features (Kollmann & Coté, 1968). Thus, the two types of *Eucalyptus* wood (EC and EV) clearly could be

Table 2. Statistics associated to the preliminary PLS-R cross-validations and test set validations for the PLS-DA classifications without treatment.

Model	R^2cv	RMSECV	R^2p	RMSEP	RPD	RER
EC	0.457	0.285	0.468	0.279	1.04	3.58
EV	0.491	0.276	0.415	0.287	1.35	3.48
C	0.862	0.141	0.881	0.139	2.79	7.19
J	0.949	0.088	0.945	0.082	4.73	12.20
P	0.913	0.114	0.900	0.119	3.23	8.40
T	0.862	0.142	0.839	0.154	2.48	6.49

Model abbreviations: see text. R^2cv, R^2p: coefficient of determination for cross and test set validation, respectively. RMSECV, RMSEP: root mean square error for cross validation and prediction, respectively. RPD: ratio of performance to deviation. RER: range error ratio.

distinguished from most of wood specimens from natural forests (J, P and T). However, the samples of *Cedrela* (C, gray squares) are mixed with *Eucalyptus* specimens in this exploratory analysis done from untreated NIR spectra.

PCA of the treated spectra promoted the separation of the species into groups according to the genetic material (Fig. 2B). *Cedrela* samples were correctly grouped as native species. NIR spectroscopy is very sensitive to variations in chemical properties and it is difficult to discriminate materials with chemical or anatomical similarity. Wood specimens from natural forests clearly differ from commercial *Eucalyptus* samples for any reasons, such as density, color, grain. In this study, all specimens present same moisture and were processed using the same procedure, so the differences captured by NIR sensor is due to intrinsic properties of each material. In short, NIR signature is able to perceive these small differences and mathematical treatments can make this information clearer. As pointed out by Yang *et al.* (2015) the non-destructive and fast separation of wood species can improve the speed of production and enable the processes to be more efficient.

In both Figs. 2A and 2B, the two types of *Eucalyptus* (EC, managed for pulp and paper industry and EV, managed for bioenergy) were grouped together and no difference between them could was highlighted.

Partial least squares discriminant analysis (PLS-DA)

In order to generate PLS-DA models capable of classifying the wood specimens by vegetal material based on NIR spectra, preliminary PLS-R models were calibrated and tested by cross-validation. The models from natural forest presented better values of statistical parameters than the models of planted forests (Table 2). The RER of PLS-R models for native woods were above 6 while the models for *Eucalyptus* were approximately 3.5 (Table 2). The PLS-R model for rosewood (J) wood presented better statistics (higher RPD and RER and lower RMSEP) and consequently the wood specimens were classified better by PLS-DA.

The classification of wood specimens from PLS-DA models both for the cross-validation and the test set yielded findings similar to the results observed by the PCAs (Table 3). The PLS-DA models presented a large percentage of correct classifications for wood specimens, except for the *Eucalyptus* that were confused between them. However, the misclassifications between *Eucalyptus* type specimens do not devalue the method since the main goal of the research was to develop models able to distinguish between the two large groups: natural (native species) and planted forests (*Eucalyptus*). Moreover, only one specimen from natural forest (Ceder) was confounded

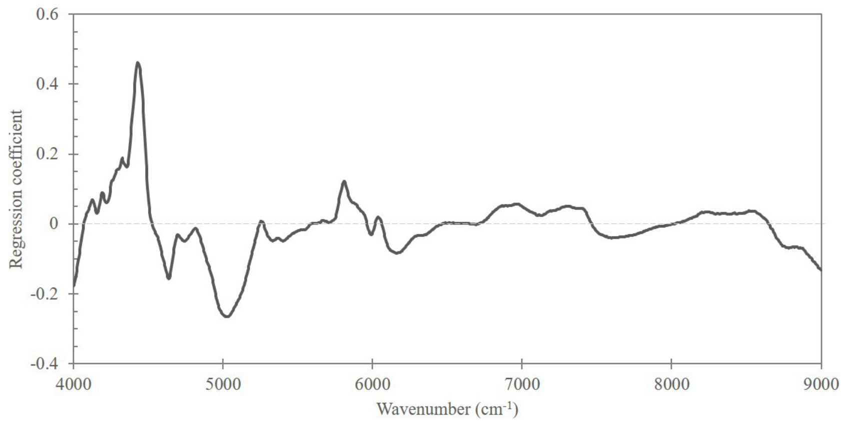

Figure 3. Absorption bands and regression coefficients of the models to predict the species classes.

Table 3. Classification of wood samples according to vegetal material by means of PLS-DA using cross-validation and test set from untreated NIR spectra.

Validation	Class of vegetal material predicted by NIR							N°	% Success
	Material	EC	EV	C	J	P	T		
Cross-validation	EC	63	27					90	70
	EV	17	73					90	81
	C		1	44				45	99
	J				89		1	90	99
	P					87	1	88	99
	T					7	80	87	92
Test set	EC	21	9					30	70
	EV	7	23					30	77
	C			15				15	100
	J				30			30	100
	P					29		29	100
	T					4	25	29	86

Table 4. Classification of wood samples according to vegetal material by means of PLS-DA using independent validation from treated NIR spectra by SNV+1d.

Validation	Class of vegetal material predicted by NIR							N°	% Success
	Material	EC	EV	C	J	P	T		
Cross-validation	EC	83	7					90	92
	EV	67	23					90	26
	C			45				45	100
	J				90			90	100
	P					88		88	100
	T						87	87	100
Test set	EC	22	8					30	73
	EV	20	10					30	33
	C			15				15	100
	J				30			30	100
	P					29		29	100
	T						29	29	100

with *Eucalyptus*, indicating that this native wood has characteristics similar, in some extent, to those of planted forest.

Among the specimens of natural forests there were incorrect classifications between T and P specimens (Table 3). Seven from 87 specimens belonging to *Apuleia* sp. group, T) was confounded and classified as *Aspidosperma* sp. wood specimens by the cross-validated models. In the model validated by test set, 14% of the T samples were misclassified as P wood samples. Besides obtaining high index of correct classification, the native species J (*Jacaranda* sp.), P (*Aspidosperma* sp.) and T (*Apuleia* sp.) were not confused with *Eucalyptus*. To sum up, the classification of native wood samples from PLS-DA carried out using untreated NIR spectra present high percentage of success (86% to 100%) indicating good efficiency of the classification models.

The PLS-DA models of Table 4 shown to be robust for classifying specimens from natural and planted forests; In this analysis, no specimen of planted forest was classified as a wood specimen from natural forest and vice versa. These results indicate that mathematical treatment can improve the signal quality of NIR spectra, allowing good classification by PLS-DA.

Again, these PLS-DA models (Table 4) present faults for classifying the varieties of the *Eucalyptus* genus. Compared to classifications of Table 3, the EV became even more mixed with EC resulting in the higher rate of misclassification (74%) while only 7 of 90 specimens of EC was confounded with EV. It is likely that these misclassifications occur because these *Eucalyptus* samples are very similar from a chemical point of view although no chemical characterization was performed in this study.

In short, the aim of distinguishing vegetal material, especially from planted or planted forests was successfully achieved. The similar findings obtained from PCAs and PLS-DAs show that it is possible to use NIR spectra for distinguishing different wood species, especially for separating unknown wood samples from natural to planted wood, but with some limitations.

Limitations

The specimens of *Cedrela* sp. wood had a greater number of samples mistakenly grouped as *Eucalyptus* wood in the PCA carried out from untreated NIR spectra. This deportment shows that the wood of some native species can be mistaken with *Eucalyptus* woods. The chemical similarity between wood from natural and planted forests can be an barrier in implementing this approach in real condition, since the chemical composition of some woods can be suchlike. This work is an approach to a preliminary study to develop a system for rapid identification of the type of wood that has been transported and sold illegally in many countries.

According to Yang *et al.* (2015) the identification of wood species is of great significance for industrial utilization as well as the quality of the final product. Moreover, this technology can be used for monitoring illegal logging. The inspection agent can record a spectrum of the sample of unknown species and compare with the database. Thus, depending on the group in which the spectrum of wood sample frame, it will be possible to classify it as originating from native or planted forest.

More studies applying this approach may include a wide range of planted and native forest species in models. Moreover, models can be developed with wood samples in different moisture content and with different surface qualities in order to generate a comprehensive database that can be efficient when used to identify the source of wood.

This study demonstrates that NIR spectroscopy has sensibility for clearly separating *Eucalyptus* from native wood and can be used for quickly and reliably identify the origin of unknown wood samples.

Concluding remarks

PCA based on untreated NIR spectra is able to clearly distinguish *Eucalyptus* wood samples from *Jacaranda* (J), *Aspidosperma* (P) and *Apuleia* (T) genus; however, most of specimens of *Cedrela* (C) wood were mixed with *Eucalyptus*. PCA of treated NIR spectra by normalization (SNV) and first derivative clearly showed two groups formed by wood samples from *Eucalyptus* and natural forests.

PLS-DA models carried out from untreated NIR spectra presented a large percentage of correct classifications (86 to 100%) for wood specimens of natural forest, except for the *Eucalyptus* samples that were confused between the two varieties. PLS-DA models based on treated NIR signatures are robust for classifying wood specimens from natural and planted forests and no specimen of planted forest was classified as specimen of natural forest and vice versa.

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