DISTINGUISHING NATIVE AND PLANTATION-GROWN MAHOGANY (*SWIETENIA MACROPHYLLA)* TIMBER USING CHROMATOGRAPHY AND HIGH-RESOLUTION QUADRUPOLE TIME-OF-FLIGHT MASS SPECTROMETRY

*Joseph Doh Wook Kim**

Graduate Student
E-mail: joseph.dw.kim@alumni.ubc.ca

Pamela Brunswick

Physical Scientist, Research
E-mail: pamela.brunswick@ec.gc.ca

Dayue Shang

Chemist
Environment and Climate Change Canada
2645 Dollarton Highway
North Vancouver, BC, V7H 1B1, Canada
E-mail: dayue.shang@ec.gc.ca

Philip D. Evans

Professor
Department of Wood Science
University of British Columbia
Vancouver, BC, V6T 1Z4, Canada
E-mail: phil.evans@ubc.ca

(Received March 2023)

Abstract. Plantation-grown mahogany (*Swietenia macrophylla*) from Fiji has been preferred as a sustainable wood source for the crafting of electric guitars because its trade is not restricted by Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), unlike *S. macrophylla* sourced from native forests. Ability to differentiate between the two wood types would deter sale of illegally harvested native-grown *S. macrophylla* to luthiers and other artisans. The chemical composition of wood is influenced by cambial age and geographical factors, and there are chemical differences between *S. macrophylla* grown in different regions. This study tested the ability of high-resolution mass spectrometry to chemotypically differentiate plantation-grown Fijian *S. macrophylla* from the same wood species obtained from native forests. Multiple heartwood specimens of both wood types were extracted and chromatographically profiled using gas and liquid chromatography tandem high-resolution quadrupole time-of-flight mass spectrometry (GC/QToF, LC/QToF). Visual comparison of mass spectral ions, together with modern analytical data-mining techniques, were employed to screen the results. Principal component analysis scatter plots with 95% confidence ellipses showed unambiguous separation of the two wood types by GC/LC/QToF. We conclude that screening of heartwood extractives using high-resolution mass spectrometry offers an effective way of identifying and separating plantation-grown Fijian *S. macrophylla* from wood grown in native forests.

Keywords: Heartwood, identification, plantation, Fiji, mahogany, *Swietenia macrophylla*, chromatography, mass spectrometry.

INTRODUCTION

True mahogany belonging to the genus *Swietenia* consists of three species, *Swietenia macrophylla*, *Swietenia mahagoni*, and *Swietenia*

* Corresponding author

humilis (Helgason et al 1996). Mahogany has been widely exploited to produce a great variety of wood products, including furniture, boats, wooden floors, paneling, and musical instruments (Anderson 2015). It is the wood of choice for electric guitars because of its lightweight, good machinability, resonance, and aesthetic appeal. Some guitars made from mahogany during the golden era (1958-1960) are favored by the world's greatest guitarists and fetch astronomical prices (>$1 million) at auction (Martinez-Reyes 2015). As a result of their overexploitation, *S. humilis* and *S. mahagoni* were listed as "species that would be in danger of extinction without strict regulation" in 1975 and 1995, respectively (Convention on International Trade in Endangered Species of Wild Fauna and Flora [CITES Appendix II]) (Cornelius et al 2004). CITES currently regards both *S. humilis* and *S. mahagoni* as commercially extinct due to their overexploitation (CITES 2021). *S. macrophylla* is still commercially important, but in 2003, it was also given the same status as *S. mahagoni* and *S. humilis* by CITES (Grogan and Barreto 2005). It is possible under CITES regulations to legally export *S. macrophylla* wood with a permit, but there is also ongoing illegal trade in the timber (Kometter et al 2004; Chimeli and Soares 2017). In addition, plantation-grown *S. macrophylla* is traded internationally. In particular, *S. macrophylla* from plantations in Fiji (where it is an introduced species) is widely available on international markets and represents the most important source of *Swietenia* wood imported into the USA (Flexport 2022). Hence, both native-grown *S. macrophylla* wood (legal and illegal) and plantation wood is potentially available to end users. One way of avoiding the possibility of using illegally logged *S. macrophylla* timber would be to simply utilize plantation-grown material. Such an approach would be assisted by the development of an effective way of identifying and separating the two wood types.

The wood identification of *Swietenia* and look-alike species received increased attention after individual species were listed by CITES, and as a result, it is now possible to separate *Swietenia* species from look-alike species. For example, *S. macrophylla* could be separated from *Carapa guianensis*, *Cedrela odorata*, and *Micropholis melinoniana* using near infrared (IR) spectroscopy (Pastore et al 2011). Both *S. macrophylla* and *S. mahagoni* could be separated from other neotropical Meliaceae with convolutional neural network analysis of end-grain images of wood (Ravindran et al 2018). All three *Swietenia* species could be distinguished from "mahogany" look-alike species belonging to the Meliaceae (*Khaya* spp. *Entandrophragma* spp, and *Lovoa trichilioides*) using direct analysis in real time (DART) ionization in combination with time-of-fight mass spectrometry (TOFMS) (Deklerck et al 2019). Furthermore, direct spray ionization injection mass spectrometry was able to distinguish *S. macrophylla* from six other hardwood species and African mahogany (Cabral et al 2012; Fasciotti et al 2015). The identification and separation of individual *Swietenia* species has received less attention and, as pointed out by He et al (2019), there is currently no direct CITES-related need for species-level separation now that all three species have been listed in CITES Appendix II. Nevertheless, identification of the three species is important for cultural and scientific reasons, and recent research has shown that they can be distinguished using machine learning models of quantitative wood anatomy data (He et al 2019) and DART-TOFMS of heartwood samples (Kane 2019). Most recently, *S. macrophylla* and *S. mahagoni* have been discriminated from each other using gas chromatography, TOFMS, and principal component analysis (PCA) (Lamichhane 2022). The same technique was also able to distinguish the two aforementioned *Swietenia* species from three look-alike species (*C. odorata, Khaya ivorensis*, and *Toona ciliata*). DART-TOFMS shows potential for identifying the provenance of individual wood species (Finch et al 2017), but to-date, research on identifying the geographic origin of *Swietenia* has relied on DNA fingerprinting (Degen et al 2013), or near IR spectroscopy (Bergo et al 2016). Both of these techniques were able to verify the geographic origin of *S. macrophylla* wood samples. Differences in the NIR spectra of *S. macrophylla* wood from

different countries reflect variation in the chemical composition of the wood specimens, suggesting that other analytical techniques, such as GC/QToF and LC/QToF, may be able to identify *S. macrophylla* wood samples from trees grown in different regions.

Recently, GC/QToF and LC/QToF in combination with machine learning proved to be very effective in distinguishing rosewoods (*Dalbergia* spp.) that are difficult to identify (Shang et al 2020; Brunswick et al 2021). We apply the same techniques here to identify and distinguish between plantation-grown Fijian *S. macrophylla* and the same wood species obtained from native forests.

MATERIALS AND METHODS

Wood Samples

Twenty different dressed-all-round Fijian mahogany samples were purchased from Paradise Timbers in Helensvale, Queensland, Australia. Each sample was 1800 mm (length) × 31 mm (width) × 11 mm (thickness). A 60-mm long specimen was cut from one end of each sample and shipped to Vancouver, Canada. Twenty-four native-grown *S. macrophylla* samples were retrieved from the University of British Columbia and FPInnovations wood collections (see Supplementary Material 1). The mahogany blocks varied in size and thickness. The average size was about 70 mm (length) × 50 mm (width) × 10 mm (thickness). The smallest were offcuts 10 mm (length) × 50 mm (width) × 10 mm (thickness) in size and the largest was 400 mm (length) × 200 mm (width) × 12 mm (thickness). All samples were conditioned in a constant climate control room at 20 ± 1°C and 65 ± 5% RH (r.h.), and they were only removed from the conditioning room immediately prior to analyses.

Preparation of Wood Samples for Chromatography

Each wood specimen was converted into chips and slivers using small carving tools, which were rinsed with 50% isopropanol among samples. Approximately 55-90 mg of wood chips were weighed on an analytical balance and transferred into 15-mL glass test tubes. A 2-mL aliquot of methanol containing 1% (v/v) formic acid was added to each test tube. All of the test tubes were vortex-mixed for 10 s, stored overnight in a fume hood, vortex-mixed again for 10 s, and then bench-top centrifuged at 5000 rpm for 2 min. The supernatant from each test tube was transferred via glass pipettes to glass vials for storage at −20 ± 5°C.

Chemicals

Acetic acid (LC-MS grade, LiChropur), formic acid (≥98% purity), daidzein, and poly(ethylene glycol) av. Mn 380-420 (PEG400) were supplied by Sigma-Aldrich (Oakville, Ontario, Canada), perfluorotributylamine (PFTBA) was purchased from Agilent Technologies Canada Inc. (Mississauga, Ontario, Canada), LC/MS grade acetonitrile and methanol obtained from Fisher Scientific (Ottawa, Ontario), and HPLC grade 2-propanol from Caledon Laboratories (Georgetown, Ontario). Caffeine-d9 (99%) was sourced from CDN Isotopes (Point-Claire, Quebec, Canada). Aqueous reagents were prepared in ultra-high purity water (MilliQ Plus).

GC/MS and GC/QToF Instrument Parameter and Analysis

GC amenable compounds were analyzed initially using an Agilent 7890A GC interfaced with an Agilent 7000C triple quadruple mass spectrometer (MS). GC separation was performed on a DB-5MS capillary column (Agilent Technologies, 30 m × 0.25 mm ID × 0.25 μm film thickness) column. The GC oven was programmed at 80°C and held for 2 min, heated to 310°C at 6°C/min, and kept at this temperature for 13 min to elute higher boiling point compounds (Table 1). The final selected conditions for GC/QToF analysis employed an Agilent 7890B GC interfaced to an Agilent 7250 QToF MS. GC separation was performed on a DB-5MS capillary column (Agilent Technologies, 30 m × 0.25 mm ID × 0.25 μm film thickness) column. The GC oven was programmed at 50°C and held for 2 min, heated to

310°C at 6°C/min, and kept at this temperature for 8 min to elute higher boiling point compounds (Table 1).

Detection of the compounds in EI + used centroid acquisition. Prior to each analytical sequence, an external mass calibration was performed using PFTBA. Additionally, a system suitability check using caffeine-d9 (100 µg/mL in acetonitrile) was performed to confirm instrument performance. Chromatographic peaks observed in total ion count scan mode (TIC) were reviewed for patterns and characteristic mass ions. For retention time locking, an extract of *Dalbergia latifolia* wood was employed with reference peak 268.073 m/z locked at 29 min. Peaks observed in blank control samples were excluded from the wood identification process.

LC/QToF Instrument Conditions and Analysis

LC/QToF analysis was performed using an Agilent Infinity 1290 LC system interfaced with 6550 iFunnelQToF MS, which was equipped with Jet Stream Technology Ion Source (AJS) controlled by MassHunter software. MS detection employed electrospray negative (ES−) mode ionization using the conditions listed in Table 2. The instrument used a fly mass correction function in the acquisition software algorithm. The time-of-flight lock mass ions for ES− at 119.03632 m/z (purine) and 980.016375 m/z (Agilent HP0 921 acetate adduct, sourced from the Agilent APITOF Reference Mass Solution) were employed for calibration. Analyte separation was performed by the reverse phase chromatographic mode with parameters listed in Table 3. System suitability (*Dalbergia latifolia*) confirmed that the signal-to-noise detection for the 267.066 m/z peak at approximately 12 min was greater than 10.

Statistical Analyses of GC/QToF and LC/QToF Data

Initially, visually observable chromatographic peaks in low-resolution GC/MS were reviewed by extraction and integration of peak areas. A canonical variate analysis (CVA) was used to formally examine this data in a multivariate way to determine differences between plantation-grown Fijian *S. macrophylla* and *S. macrophylla* wood grown in native forests. Statistical computation for CVA was performed using Genstat (v. 19). Further analysis of wood extracts was performed by LC and GC/QToF, with the collected data imported into Agilent's Unknowns Analysis software, deconvoluted using the SureMass

Table 1. Instrument parameters for operation of GC/QToF in EI + mode.

Component/Parameter	Details/Value
Column	Agilent DB-5MS + 10 m DG, 30 m, 0.25 mm id, 0.25 µm film
Injection	0.5 µL pulsed splitless
Purge flow to split vent	50 mL/min for 1 min
Initial temp.	250°C
Oven temp. program GC/MS	80°C hold for 2.0 min, 6°C/min to 310°C, hold for 13 min
—	total run time approximately 53 min
Oven temp. program GC/QToF	70°C hold for 2.0 min, 6°C/min to 310°C, hold for 12 min
—	total run time approximately 42 min
Carrier gas	1 mL/min helium
Interface temp.	280°C
EI+ (Electron ionization)	70 EV at 250°C
Quad temp.	150°C
TOF tune	1 GHz extended dynamic range
Scan	60-1000 m/z (GCMS) and 50-900 m/z (GC/QTOF)
Spectra acquisition	1 Hz in centroid
Scan rate	2.0 spectra/s
Microchannel plate (MCP)	750 V (variable to tune)
Photomultiplier tube (PMT)	500 V (variable to tune)

Table 2. Instrument parameters for LC/QToF analysis.

Component/Parameter	Details/Value
Ionization mode	ES−
Scan	90-1100 m/z
Data collect	1.5-32.0 min
Nebulizer	30 psig
VCap	3500
Nozzle V	1350
Fragmentor	365
Gas temp./flow	230°C (12 L/min)
Sheath gas/flow	350°C (11 L/min)
LC column	Agilent Poroshell 120 SB-C18 (2.7 μm, 2.1 × 100 mm)
LC flow	0.4 mL/min
LC post time	0.5 min
TOF lock mass (purine)	ES+ 121.0509 m/z; ES− 119.03632 m/z
TOF lock mass (HP0921)	ES+ 922.0098 m/z; ES− 980.016375 m/z

Algorithm, and converted to common event format (CEF) files for import into Mass Profiler Professional (MPP). The unbiased nature of the machine learning process of MPP was used to perform preliminary alignment frequency filtering of discriminating entities and ANOVA ($p > 0.05$) of data. PCA scatter plots were created to help visualize the output of the algorithms.

Total Extractive Contents and Light Microscopy

The preparation of wood and extraction of solvent soluble extractives were carried out according to TAPPI standards T 264 om-88 and T 204 om-88, respectively (Tappi 1993). Eight mahogany samples (four Fijian *S. macrophylla* samples and four native-grown *S. macrophylla samples*) were randomly selected to determine their total extractive contents. Wood samples were selected and split to create thin rod-like pieces of wood measuring approximately 2 mm^2 × 15 mm. Pieces of wood from each sample, approximately 3 g, were separately ground in a Wiley-mill to pass a 40 mesh sieve (0.4 mm). The Wiley-mill was thoroughly cleaned among samples. Wood flour, approximately 2 g from each sample, was placed in separate cellulose thimbles and Soxhlet-extracted with 1:2 ratio of ethanol toluene for not less than 24 extraction cycles over a 5-h period. The flasks were removed from the apparatus and the solvent allowed to partially evaporate in the extraction flask to a volume of 20 mL. The extract was transferred to a tared weighing dish with minimal amount of fresh solvent used. The dish was oven-dried for 1 h at 115 ± 5°C, cooled in a desiccator, and then weighed to the nearest 0.1 mg. The extractive content was calculated as follows: Total extractives, % = ([oven-dry weight of extract − oven-dry weight of blank residue]/oven-dry weight of wood) × 100.

Table 3. Conditions for the reverse phase LC/QToF separation.

Time (min)	% A: 0.1% v/v acetic acid in ultrapure water	%B: 0.1% v/v acetic acid, 2% v/v 2-propanol in acetonitrile
0.5	95.0	10.0
14.0	50.0	50.0
17.0	1.0	99.0
20.0	1.0	99.0
20.1	95.0	10.0
23.0	95.0	10.0

Wood blocks measuring 20 mm (length) × 8 ± 2 mm (width) × 8 ± 2 mm (thickness) and cut from plantation and native-grown *S. macrophylla* wood were placed in separate glass beakers containing ultrapure distilled water for 3 d. Water-saturated wood blocks were placed one-at-a-time in the microtome clamp of a sliding sledge microtome (Spencer Lens Co) and transverse sections, approximately 20 μm thick were cut from blocks using a microtome blade-holder (Feather® No. 160) containing a fresh disposable microtome blade (Feather® Type S35). Microtome sections were immersed in a 10% ethanolic solution of 1% safranin for approximately 5 min and dehydrated in 100% ethanol for 15 min. Sections were permanently mounted on glass slides using synthetic resin media (DPX Mountant, Aldrich) and each section was covered with a glass cover-slip. Slides were examined with a light microscope (Carl Zeiss Universal Fluorescent Microscope) equipped with a digital camera (Olympus DP71). Images of transverse surfaces were saved as TIFF files (Christy et al 2005).

RESULTS

Total Extractive Contents and Light Microscopy

The reference wood specimens of native-grown (sample #1, #13, #15, and #18 in supplementary material) and Fijian plantation *S. macrophylla* looked similar, but not identical under the microscope. Figure 1 shows transverse sections of both wood types. One difference between the two woods is that the lumens of vessels in plantation-grown *S. macrophylla* were largely free of resin-like deposits, whereas approximately 10% of vessels in native-grown wood contained deposits (Fig 1). However, there was no significant ($p > 0.05$) difference in extractive contents of the two wood types: the extractive content of plantation-grown Fijian *S. macrophylla* was 4.7% (6.9-1.6; 0.026; max-min, St Dev), whereas that of wood from native-grown trees was 5.5% (8.6-2.9; 0.024).

GC/MS

Preliminary analysis of heartwood extractives from the two wood types analyzed by GC/MS (EI+) showed close similarity in their TIC chromatography. The scans were reviewed visually and by instrument screening software for potential differences between the two wood groups. Selected peaks were extracted, integrated, and examined. The extracted ions that best discriminated between native-grown and Fijian *S. macrophylla* eluted at retention times 14.1, 19.2, and 22.2 min, corresponding to mass ions at 152.2, 182.3, and 181.2 m/z, respectively. Peak response areas for these ions from each wood sample were subject to CVA after log (ln) transformation using the statistical software package Genstat (Campbell and Atchley 1981). CVA has been used for identification and separation of two anatomically similar eucalyptus species (Evans et al 2008) and canonical correlation analysis has been used to model variation of wood properties of tepozán (*Buddleja cordata*) across its natural range in Mexico (Aguilar-Rodríguez et al 2006). Figure 2 plots the CVA scores for native-grown and Fijian *S. macrophylla.* A negative value for the CVA score indicates that the specimen is Fijian plantation-grown *S. macrophylla*, whereas a positive value indicates that the specimen is native-grown *S. macrophylla*. The larger the absolute values, the more certain the classification.

GC/QToF

Further analysis of wood extracts was performed by high-resolution GC/QToF (EI+). Overall, chromatographic results were not visually distinctive and did not easily separate native-grown and Fijian plantation-grown *S. macrophylla*. Peak responses varied within each study group and no

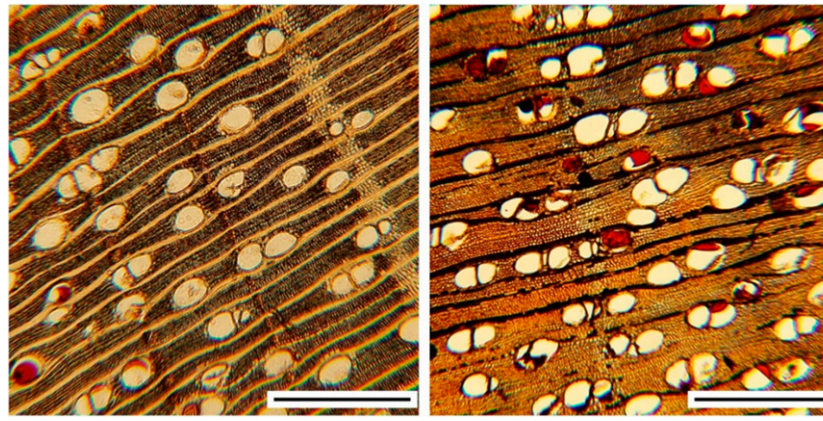

Figure 1. Transverse sections of plantation-grown Fijian mahogany (left) and native-grown *S. macrophylla* (right). Scale bars = 1 mm.

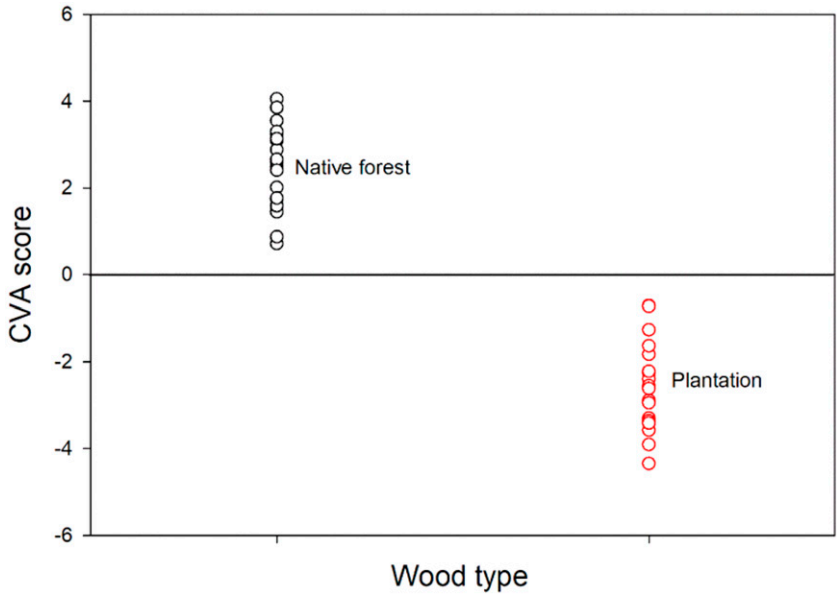

Figure 2. Canonical variate analysis (CVA) scores for native-grown and Fijian plantation-grown *S. macrophylla* analyzed by GC/MS.

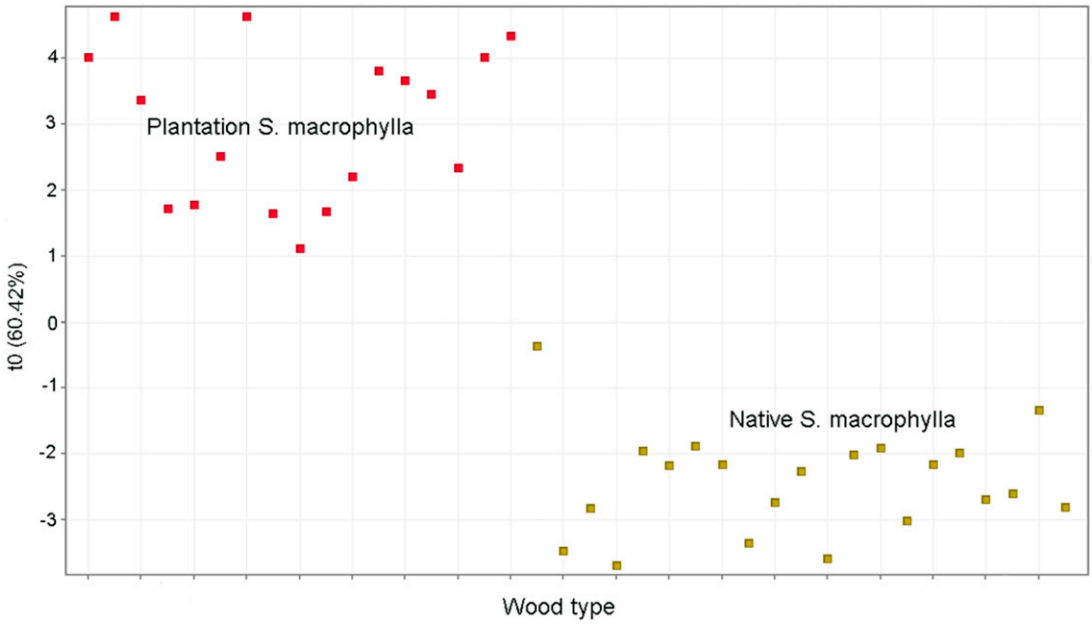

Figure 3. Three-dimensional principal component analysis (PCA) 2D scatter plots of EI + GC/QToF data for plantation and native-grown *S. macrophylla.*

signature peak or ion was found to be definitive for identification purposes. However, the original mass ions observed by low-resolution GC/MS were supported by further observation under different conditions during GC/QToF analysis, at the adjusted retention times of 9.5, 13.1, and 15.5 min, with corresponding mass ions at 151.039, 182.057, and 181.049 m/z. Statistical analysis of these peaks again showed a similar distinction between the Fijian plantation-grown *S. macrophylla* and all native-grown specimens.

Application of instrument machine learning software was able to exploit the collected data to select discriminate entities in an unbiased manner. The identification of the source of the specimens involved deconvolution of complex chromatographic data in Agilent Unknowns analysis, followed by frequency filtering and statistical analysis in MPP. Results showed discrimination between the two wood types.

A partial least squares (PLS) scores-plot of data-mined GC/QToF results showed a distinction between native-grown *S. macrophylla* samples from samples grown in plantation in Fiji (Fig 3). A two-dimensional PCA plot from GC/QToF data clearly demonstrated greater variability within the native-grown *S. macrophylla* wood compared with plantation wood (Fig 4). However, 95% confidence ellipses associated with each wood type, indicate clear separation of native-grown *S. macrophylla* samples and those grown in plantation in Fiji, which show little within-group variation.

LC/QToF

Heartwood extracts from native- and plantation-grown *S. macrophylla* were further analyzed by LC/QToF in electrospray negative mode (ES−). Both two-dimensional (Fig 5) and three-dimensional (not shown) PCA plots distinguished native-grown *S. macrophylla* wood from Fijian

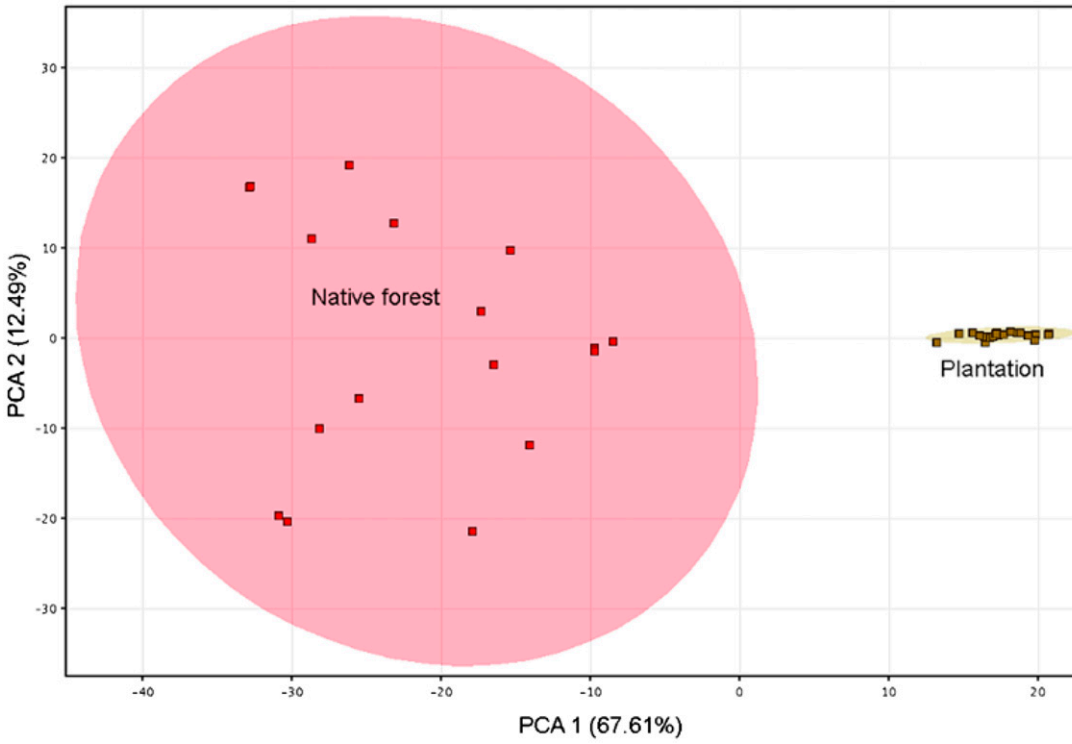

Figure 4. PCA 2D scatter plots of EI + GC/QToF data showing 95% confidence limits for data from plantation and native-grown S. *macrophylla*.

plantation-grown *S. macrophylla* wood. Again, greater variability within the native wood type was observed.

An unvalidated PLS discriminant analysis (PLS-DA) model also distinguished native-grown from Fijian plantation *S. macrophylla* using the set of reference samples (Fig 6).

DISCUSSION

The aim of this research was to determine whether gas/liquid chromatography combined with high-resolution mass spectrometry could offer a robust approach to distinguishing *S. macrophylla* grown in plantation in Fiji from wood sourced from native forests. Chromatography has long been used to help identify commercially important wood species. Initial research focused on identifying woods that were difficult to separate using anatomical features, eg *Shorea* spp. (Samapuddhi 1957; Fanega and Mule 1973; Kato and Hishiyama 2007), *Pinus* spp. (Seikel et al 1965; Swan 1966), *Acer* spp. (Park and Kim 1984), and three *Khaya* species, one of which caused dermatitis in furniture factories in the United Kingdom (Morgan and Orsler 1967). Application of gas chromatography and mass spectrometry initially focused on identifying wood with commercially important characteristics related to heartwood extractives, eg wood color (Swan 1966), aroma (Nonier et al 2006), and the flavor of woods used as ice-cream sticks (Sudarat and Harper 2004). Some of the early combined GC/MS studies demonstrated the potential of the technique to identify different wood genera (Challinor 1995; Nonier et al 2006) and such studies were the antecedents to the more advanced techniques used to identify endangered woods listed by CITES, including *Swietenia* (Lamichhane 2022), *Dalbergia* (Hou et al 2018; Shang et al 2020; Brunswick et al 2021), and *Pterocarpus* (Zhang et al 2019).

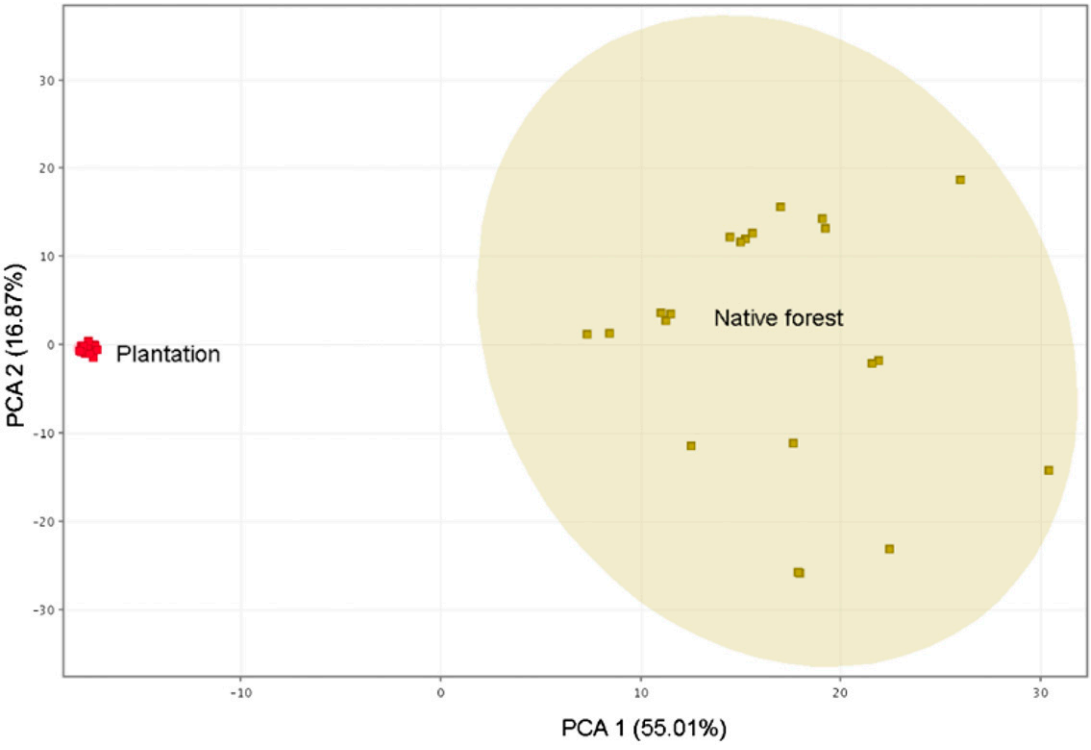

Figure 5. PCA 2D scatter plots of ES− LC/QToF data showing 95% confidence limits for wood samples from plantation and native-grown *S. macrophylla*.

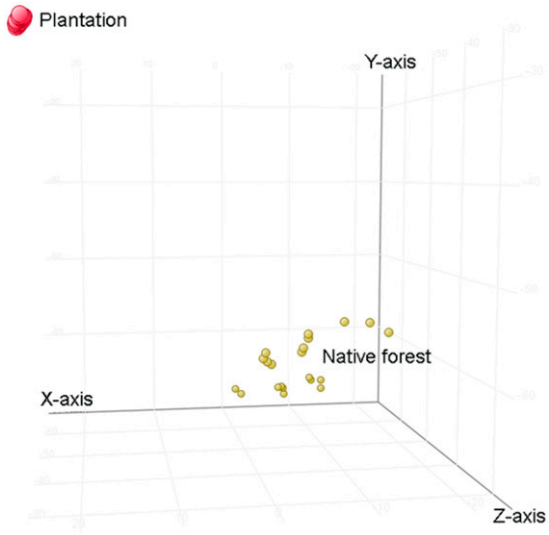

Figure 6. Partial least squares discrimination model of plantation and native-grown *S. macrophylla* using LC/QToF ES− data.

LC/MS is a more recent branch of the field and has been used to identify wood to the genus and species levels and to determine the geographical origin of Spanish cedar (*Cedrela odorata*) and Norway spruce (*Picea abies*) (Surowiec et al 2004; Kite et al 2010; Buche et al 2021; Creydt et al 2021, 2022). Our finding that LC/QToF and multivariate data analysis can identify and separate native *S. macrophylla* and plantation-grown Fijian *S. macrophylla* accords with previous research by Creydt et al (2021, 2022) on the geographical separation of Spanish cedar and Norway spruce. In addition, we show that similar separation of native and plantation-grown Fijian mahogany can also be achieved using GC/QToF. Overall, it was encouraging to find that the two very different approaches, one (LC) screening for the more hydrophilic, negative ion-forming compounds, and the other (GC) screening for the more volatile, hydrophobic, positive ion-forming compounds, were both able to distinguish the two *Swietenia* wood types from different sources. This finding should encourage further research on the use of this approach, ie chromatographic separation followed by mass spectrometry, to identify the geographical origin of wood species.

The listing of *S. macrophylla* by CITES and associated trade regulations led to a flourishing illegal trade in *S. macrophylla* wood exported under the category "other tropical timber species" (Chimeli and Soares 2017). This illegal trade coexists with a legal "certified" trade in *S. macrophylla* and also trade in plantation-grown *S. macrophylla*. In addition, small artisanal businesses making guitars may have stockpiles, albeit dwindling, of *S. macrophylla* wood accumulated prior to current trade restrictions (Martinez-Reyes 2015). These businesses, lacking the knowledge and control over supply chains of larger manufacturers, are afraid to use mahogany because they fear confiscations or fines (Dudley 2011). Our finding that GC/LC/QTOF can separate native and plantation-grown Fiji mahogany provides a potential solution to this issue because the machine learning software, which was very helpful in separating plantation-grown Fijian *S. macrophylla* from native-grown wood, is compatible with both low- and high-resolution instrumentation. In fact, single quadruple GC/MS instrumentation is a staple of analytical laboratories worldwide and the cost of GC/MS analysis is as little as $60 per sample, a faction of the cost of a custom-made mahogany electric guitar ($5000-$10,000) or the fines levied on companies using illegally harvested mahogany (Martinez-Reyes 2015). Further work to build a mahogany specific spectral library, validate the method with unknown testing samples, and transfer of technology to environmental labs is needed to develop such an analytical service, which would help the guitar industry and other end users of mahogany to avoid issues associated with the use of mahogany wood that is not sustainably harvested.

CONCLUSIONS

We conclude that screening of heartwood extractives by gas or liquid chromatography with high-resolution mass spectrometry, in combination with multivariate statistical analysis of discriminating ions, offers an effective way of separating plantation-grown Fijian *S. macrophylla* from the same wood species grown in native forests. Our findings offer a potential solution to environmentally conscious manufacturers of guitars who wish

to use plantation-grown Fijian mahogany rather than being exposed to the liability associated with using illegally logged native-grown mahogany. Further research is needed to extend our work to plantation-grown mahogany from other parts of the world, and to examine the feasibility and costs of developing an analytical service and associated databases to identify and separate plantation-grown mahogany from native-grown timber.

ACKNOWLEDGMENT

We thank Drs. Daniel Cuthbertson and Marcus Kim of Agilent Technologies Inc., Jeffrey Yan of ECCC, Dr. Chip (Robert) Cody of JEOL Inc., and Bill Leggate of DAF for material support or technical assistance. P.D.E. thanks Viance LLC, Tolko, FPInnovations, Faculty of Forestry (University of British Columbia), and the Government of British Columbia for supporting his BC Leadership Chair in Advanced Forest Products Manufacturing Technology.

REFERENCES

Aguilar-Rodríguez S, Terrazas T, Lopez-Mata L (2006) Anatomical wood variation of *Buddleja cordata* (Buddlejaceae) along its natural range in Mexico. Trees (Berl) 20(2):253-261.

Anderson JL (2015) Mahogany: The costs of luxury in early America. Harvard University Press, Cambridge, MA.

Bergo MC, Pastore TCM, Coradin VTR, Wiedenhoeft AC, Braga JWB (2016) NIRS identification of *Swietenia macrophylla* is robust across specimens from 27 countries. IAWA J 37(3):420-430.

Brunswick P, Cuthbertson D, Yan J, Chua CC, Duchesne I, Isabel N, Evans PD, Gasson P, Kite G, Bruno J, van Aggelen G, Shang D (2021) A practical study of CITES wood species identification by untargeted DART/QTOF, GC/QTOF and LC/QTOF together with machine learning processes and statistical analysis. Environ Adv 5:100089.

Buche G, Colas C, Fougère L, Giordanengo T, Destandau E (2021) Untargeted UHPLC-Q-TOF-HRMS based determination of discriminating compounds for oak species *Quercus robur* L. and *Quercus petraea* Liebl. identification. Phytochem Anal 32(5):660-671.

Cabral EC, Simas RC, Santos VG, Queiroga CL, da Cunha VS, de Sá GF, Daroda RJ, Eberlin MN (2012) Wood typification by Venturi easy ambient sonic spray ionization mass spectrometry: The case of the endangered mahogany tree. J Mass Spectrom 47(1):1-6.

Campbell NA, Atchley WR (1981) The geometry of canonical variate analysis. Syst Biol 30(3):268-280.

Challinor JM (1995) Characterisation of wood by pyrolysis derivatisation—Gas chromatography/mass spectrometry. J Anal Appl Pyrolysis 35(1):93-107.

Chimeli AB, Soares RR (2017) The use of violence in illegal markets: Evidence from mahogany trade in the Brazilian Amazon. Am Econ J Appl Econ 9(4):30-57.

Christy AG, Senden TJ, Evans PD (2005) Automated measurement of checks at wood surfaces. Measurement 37(2):109-118.

CITES (2021) CITES trade controls to take effect for mahogany. https://cites.org/eng/news/pr/2003/031111_mahogany.shtml (22 May 2022).

Cornelius JP, Wightman KE, Grogan JE, Ward SE (2004) Tropical Ecosystems. *Swietenia* (American Mahogany). Encyclopedia of Forest Sciences, Elsevier. 1720-1726 pp.

Creydt M, Lautner S, Fromm J, Fischer M (2022) Wood profiling by non-targeted liquid chromatography high-resolution mass spectrometry: Part 2, detection of the geographical origin of spruce wood (*Picea abies*) by determination of metabolite pattern. J Chromatogr A 1663:462737.

Creydt M, Ludwig L, Köhl M, Fromm J, Fischer M (2021) Wood profiling by non-targeted high-resolution mass spectrometry: Part 1, metabolite profiling in Cedrela wood for the determination of the geographical origin. J Chromatogr A 1641:461993.

Degen B, Ward SE, Lemes MR, Navarro C, Cavers S, Sebbenn AM (2013) Verifying the geographic origin of mahogany (*Swietenia macrophylla* King) with DNA-fingerprints. Forensic Sci Int Genet 7(1):55-62.

Deklerck V, Mortier T, Cody R, Goeders N (2019) A protocol for automated timber species identification using metabolome profiling. Wood Sci Technol 53(4):953-965.

Dudley KM (2011) Luthiers: The last endangered species. *The New York Times* op-ed, 25 October. www.nytimes.com/2011/10/26/opinion/are-guitar-makers-an-endangered-species.html (12 July 2022).

Evans P, Heady R, Cunningham R (2008) Identification of yellow stringybark (*Eucalyptus muelleriana*) and silvertop ash (*E. sieberi*) wood is improved by canonical variate analysis of ray anatomy. Aust For 71(2):94-99.

Fanega SM, Mule EI (1973) Chemotaxonomic contribution to the question of the identity of Tiaong, *Shorea agsaboensis* Stern (Dipterocarpaceae). Philippine Lumberman 19(7):14, 16, 18.

Fasciotti M, Alberici RM, Cabral EC, Cunha VS, Silva PR, Daroda RJ, Eberlin MN (2015) Wood chemotaxonomy via ESI-MS profiles of phytochemical markers: The challenging case of African versus Brazilian mahogany woods. Anal Methods-UK 7(20):8576-8583.

Finch K, Espinoza E, Jones FA, Cronn R (2017) Source identification of western Oregon Douglas-fir wood cores using mass spectrometry and random forest classification. Appl Plant Sci 5(5):1600158.

Flexport (2022) U.S. import and export data. Mahogany (*Swietenia* spp.) HS Code 440721. https://www.flexport.com/data/hs-code/440721-mahogany-sawn-chipped-lengthwise-sliced-peeled (22 May 2022).

Grogan J, Barreto P (2005) Big-leaf mahogany on CITES Appendix II: Big challenge, big opportunity. Conserv Biol 19(3):973-976.

He T, Marco J, Soares R, Yin Y, Wiedenhoeft AC (2019) Machine learning models with quantitative wood anatomy data can discriminate between *Swietenia macrophylla* and *Swietenia mahagoni*. Forests 11(1):36.

Helgason T, Russell SJ, Monro AK, Vogel JC (1996) What is mahogany? The importance of a taxonomic framework for conservation. Bot J Linn Soc 122(1):47-59.

Hou S, Huang X, Ma Y, Huang F, Lin X, Ma Y, Zhu Z, Luo H, Wu H (2018) Identification of *Dalbergia odorifera* and *Dalbergia* spp by solid phase microextraction-gas chromatography-mass spectrometry. Chinese J Chromat 36(5):493-498.

Kane PE (2019) Mahogany: New research on the wood of choice in early Rhode Island furniture. Yale University Art Gallery Bulletin. 69-77 pp.

Kato A, Hishiyama S (2007) Identification of red meranti based on the heartwood extractives. Pages 20-22 *in* International Symposium on Development of Improved Methods to identify Shorea species wood and its origin, IUFRO, Tokyo (14 September 2007).

Kite GC, Green PWC, Veitch NC, Groves MC, Gasson PE, Simmonds MSJ (2010) Dalnigrin, a neoflavonoid marker for the identification of Brazilian rosewood (*Dalbergia nigra*) in CITES enforcement. Phytochemistry 71(10):1122-1131.

Kometter RF, Martinez M, Blundell AG, Gullison RE, Steininger MK, Rice RE (2004) Impacts of unsustainable mahogany logging in Bolivia and Peru. Ecol Soc 9(1):1-20.

Lamichhane DD (2022) Identification of five wood species of the Meliaceae family on the basis of their wood anatomical and chemical characteristics. M.Sc. Thesis, Université Laval. Quebec City, Quebec, Canada. 154 pp.

Martinez-Reyes J (2015) Mahogany intertwined: Enviromateriality between Mexico, Fiji, and the Gibson Les Paul. J Mater Cult 20(3):313-329.

Morgan JW, Orsler RJ (1967) A simple test to distinguish *Khaya anthotheca* from *K ivorensis* and *K grandifoliola*. J Inst Wood Sci 1(18):61.

Nonier MF, Vivas N, Vivas de Gaulejac N, Absalon C, Soulié P, Fouquet E (2006) Pyrolysis—Gas chromatography/mass spectrometry of *Quercus* sp. wood: Application to structural elucidation of macromolecules and aromatic profiles of different species. J Anal Appl Pyrolysis 75(2):181-193.

Park KW, Kim SS (1984) A study on the wood identification of the genus Acer in Korea—Especially on the method by thin layer chromatography of lipid in heartwood. J Korean Soc For Sci 65(1):60-67.

Pastore TCM, Braga JWB, Coradin VTR, Magalhães WLE, Okino EYA, Camargos JAA, de Muñiz GIB, Bressan OA, Davrieux F (2011) Near infrared spectroscopy (NIRS) as a potential tool for monitoring trade of similar woods: Discrimination of true mahogany, cedar, andiroba, and curupixá. Holzforschung 65(1):73-80.

Ravindran P, Costa A, Soares R, Wiedenhoeft AC (2018) Classification of CITES-listed and other neotropical Meliaceae wood images using convolutional neural networks. Plant Methods 14(1):1-10.

Samapuddhi K (1957) A note on preliminary studies in some methods of identifying the timbers of *Pentacme siamensis*, Kurz., *Shorea obtusa* Wall., and *Shorea robusta*, Gaertn. f. Publication Royal Forest Department, Ministry of Agriculture, Bangkok.

Seikel MK, Hall SS, Feldman LC, Koeppen RC (1965) Chemotaxonomy as an aid in differentiating wood of eastern and western white pine. Am J Bot 52(10):1046-1049.

Shang D, Brunswick P, Yan J, Bruno J, Duchesne I, Isabel N, van Aggelen G, Kim M, Evans PD (2020) Chemotyping and Identification of protected *Dalbergia* timber using gas chromatography quadrupole time of flight mass spectrometry. J Chromatogr A 1615:460775.

Sudarat J, Harper WJ (2004) Identification of volatile flavor compounds in wooden ice cream sticks originated from different geographical locations. Milchwissenschaft 59(9-10):530-532.

Surowiec I, Nowik W, Trojanowicz M (2004) Identification of "insoluble" red dyewoods by high performance liquid chromatography–photodiode array detection (HPLC-PDA) fingerprinting. J Sep Sci 27(3):209-216.

Swan EP (1966) Chemical methods of differentiating the wood of several western conifers. Forest Prod J 16(1): 51-54.

Technical Association for the Pulp and Paper Industry (TAPPI) (1993) TAPPI standards and suggested methods, TAPPI T264OM-88; TAPPI T204 OM-88. Tech Assoc Pulp Pap Ind, New York, NY. 754 pp.

Zhang M, Zhao G, Guo J, Liu B, Jiang X, Yin Y (2019) A GC-MS protocol for separating endangered and non-endangered *Pterocarpus* wood species. Molecules 24(4): 799.

SUPPLEMENTARY MATERIAL

Supplementary Material 1. Dimensions and origins of native-grown *Swietenia macrophylla.*

Sample	UBC ID #	Dimensions (mm)	Origin
1	7522	59.5 × 14.5 × 2.1	Honduras
2	7698	54 × 19 × 1.3	Honduras
3	7711	54 × 19 × 1.3	Honduras
4	928	14.5 × 10 × 2.5	Honduras
5	2110	14 × 8 × 1	Honduras
6	1505	12 × 6.5 × 1.3	Honduras
7	494	8 × 3 × 1	Honduras
8	2111	10.5 × 7.5 × 1	Honduras
9	2001	10 × 7.5 × 2.5	Honduras
10	2988	14.5 × 7 × 1	Honduras
11	3027	10 × 6 × 1.3	Honduras
12	3346	9.5 × 5 × 1.5	Honduras
13	8583	10 × 6 × 2.4	Honduras
14	8584	10 × 6 × 1.5	Honduras
15	8841	13.7 × 6 × 4	Central America
16	9005	14 × 5 × 1	Honduras
17	9281	10.5 × 7.5 × 1	Honduras
18	9676	10.5 × 7 × 1	Honduras
19	10,046	5.8 × 5 × 1	Honduras
20	7826	20 × 12.5 × 0.5	Central America
21	7831	20.5 × 15 × 0.5	Central America
22	FPInnovations 1	11 × 7 × 1	Central America
23	FPInnovations 2	11 × 6.5 × 1	Mexico
24	FPInnovations 3	14 × 6.5 × 1	Mexico