WorldForestID: Addressing the need for standardized wood reference collections to support authentication analysis technologies; a way forward for checking the origin and identity of traded timber

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Societal Impact Statement  
Forest products are the most used inedible renewable resource, but supplies are finite. It is difficult to know which tree species are in wood products or where they come from. Scientific evidence is needed to support or refute origin and species claims in traded products. We describe the building of a geo-referenced wood reference collection (xylarium) supported by herbarium voucher specimens. The WorldForest ID program, hereinafter referred to as WFID (www.worldforestid.org), is embarking on large-scale field collections of wood samples suitable for science-based authentication technologies. By coordinating with regulatory and enforcement authorities in both producer and consumer countries the WFID xylarium is legally robust and commercially relevant.

Summary  
We describe a program called WorldForestID which is being developed to monitor and support authentication and compliance in international trade of timber products. The program is being run by a consortium of government and non-government organizations: US Forest Service International Programs (USFS IP), Royal Botanic Gardens, Kew, Forest Stewardship Council (FSC), Agroisolab, and World Resources Institute (WRI). Initial funding has come from the US Department of State, USFS IP, US Department of Agriculture Animal and Plant Health Inspection Service, Forest Stewardship Council, and the UK Department for Environment, Food and Rural Affairs (Defra). The aim is to build a comprehensive collection of internationally traded timber species. The collection is used as reference material to validate forest products. Although there are a large number of xylaria (wood collections, Index Xylariorum IV) around the world, many of the specimens do not provide geo-locations suitable as reference material for pinpointing provenance, many lack-associated herbarium vouchers and some are misidentified. The samples being collected in this program address these issues and include bark, sapwood, and heartwood, ensuring...
that the material collected is suitable for current and future scientific analysis. We describe the process of collection and validation from field to laboratory and the advantages and disadvantages of the main techniques used to ascertain/verify identity and provenance. Ultimately, we envisage the day that scientific methods will be used routinely and successfully by timber traders, manufacturers, retailers, and law enforcement to accept or reject identity and provenance claims on internationally traded timber and forest products and, where necessary, to support prosecutions when laws such as EU Timber Regulations, Lacey Act and CITES are infringed.

**KW**
DART-TOFMS, illegal logging, international trade, provenance, SIRA (stable isotope ratio analysis), wood anatomy, wood identification, xylarium

## 1 | INTRODUCTION

Forest products are humankind’s most used inedible renewable resource, but supplies are not inexhaustible. Deforestation, either for utilization or to clear land for other purposes, has far-reaching environmental effects including reducing biodiversity, pushing individual species toward extinction, destroying habitats, and changing the climate and soil. The full economic value of timber is often unrecognized, and there is a very high volume of illegal trade in wood products that can only be quantified when confiscations have taken place (e.g., rosewood comprises 35% of the monetary value of confiscated illegal wildlife trade, UNODC, 2016a). Supply chains are complicated, often covering long distances and lead times: trees are routinely harvested at one location, transported through one, two or more countries before being processed into manufactured products such as furniture, flooring, or paper. End products are subsequently exported to consumers in distant countries. It may be the case for some supply chains that verification of origin is, for all practical purposes, impossible within existing certification and documentation methods. This means that the truth of two fundamental authentication attributes of timber—harvest origin and species—may remain uncertain or invisible, even when complex investigatory resources or due diligence systems are applied.

Although there is legislation in many countries aimed at regulating trade in timber and its products, there remains a high level of global illegal activity. In tropical forests, 50–90 percent of forestry activities is illegal in sourcing or trade practices (Van der Werf et al., 2009). There are also problems with illegal extraction of temperate species such as larch (Larix spp., Blanc-Jolivet et al., 2018) and oak (Quercus spp., Schroeder et al., 2016). It is impossible to regulate trade without the ability to assess whether origin and identity claims are correct. Currently, investigative tools focus on documentation control, such as the veracity of the chain of custody, forest permits, and certifications. The vast array of legitimate timber traders has conventionally relied on certification and audit as the best means for validating the claims made about the origin and species of traded timber.

Until recently little use has been made of scientific evidence to support due diligence with respect to traded timber, although over the last 5 years there have been concerted efforts to change this (Dormontt et al., 2015; Koch et al., 2015; Schmitz et al., 2020; Schmitz, Beeckman, et al., 2019; Schmitz, Blanc-Jolivet, et al., 2019; UNODC, 2016b). In this article, we describe the development of the World Forest ID program (WFID), a working prototype for building geo-referenced, wood, and foliage reference collections. WFID has embarked on developing protocols for large scale field collections, comprehensive processing, and sample curation with the aim of providing wood samples suitable for an increasing range of science-based authentication technologies capable of validating origin and species. WFID focused technologies are those that have been shown to identify species and/or provenance of test samples effectively and reliably when compared to reference data. These include wood anatomy, stable isotope analysis, Direct Analysis in Real Time Time-of-Flight Mass Spectrometry (DART-TOFMS), and genetic approaches. These methods have been described in the UNODC Best Practices Guide for Forensic Timber Identification (2016) and most recently in the GTTN data analysis guide (Schmitz et al., 2020). Importantly, in addition to supporting the needs of timber trade due diligence requirements, WFID sampling and handling protocols have been designed in collaboration with the US Department of Justice and UK Competent Authorities to be legally robust, meeting the needs of regulatory and enforcement authorities in the preparation and delivery of court action in producer and consumer countries.

WFID collections begin with the development and approval of certified plans prior to teams extracting geo-referenced timber samples in the field. After collection, geo-referenced samples are sent to Kew where they are quarantined, curated, and then submitted to WFID partner laboratories for analysis with results available to enforcement and other end-users via the WFID database housed at the University of Connecticut. In addition to field-collected samples, we outline how improving wood reference collections will underpin and enhance the usability of scientific data derived from them. Finally, although there has been encouraging progress, we emphasize that the wide range of active participants in trading timber must be encouraged and supported to adopt science-based wood authentication.
Better communication and understanding will be needed between traders, legislators, scientists—and the wider timber consumer public—before accurate labeling of timber is achieved and the trade-in products resulting from illegal logging is effectively addressed.

2 | THE NEED FOR ACCURATE PROVENANCE AND IDENTITY

Without knowledge of the identity and provenance of the woods in a product, it is impossible to know whether they are derived from legitimate legal and sustainable sources. Laws and regulations in many countries require timber importers to have completed and made available documents demonstrating that appropriate due diligence has been carried out describing the chain of custody of the traded timber. Different regulatory systems approach due diligence in different ways, for example, which participants in a supply chain must be identified as part of the process; and when in the supply chain due diligence regulations apply. For example, EU Timber Regulations (EUTR)—UKTR post-Brexit—require that due diligence declarations apply only when and if a product is first placed on a market. Other regulations, such as the Lacey Act in the USA require importers to correctly declare origin and species at the point of entry of their imported timber consignments. This is not as straightforward as it looks given that participants further up supply chains may be more or less anonymous, making the declaration task of US importers more challenging. Many taxa, such as oak (Quercus) and rosewood (mainly Dalbergia, also Pterocarpus, Guibourtia), have very wide geographic distributions and origin cannot be assigned from knowing the identity of species alone. Also with regard to species, precise identification can be difficult or impossible especially without expert knowledge (Gasson, 2011). Further complications include the need for taxonomic revision of many, especially tropical genera traded in the international market. The genus Dipteryx, with well-known wood anatomy (Gasson, 1999) is a good example where identification of species is problematic. Dipteryx odorata, one of 13 or 14 species in the genus (Carvalho et al., 2020; Plants of the World Online) has been claimed to be exported from Peru, but morphology and molecular evidence suggest that this species is not actually present there (Garcia-Davila et al., 2020; Honorio Coronado et al., 2020). Incorporating these taxonomic refinements into trade and legislation on a large scale for many tree taxa is daunting. Determination of origin and species is thus a hard task for many traders, especially for those in non-integrated supply chains who rely on fallible paperwork alone to fulfill their harvest-origin and species declarations. For regulatory authorities engaged with enforcing the relevant legislation the task is harder still.

3 | IDENTITY: WHAT IS IT?

This is the first question most people ask about a wooden item and it can be very difficult to answer. In many cases, an answer such as beech (Fagus), oak (Quercus), ash (Fraxinus), or teak (Tectona) will suffice, although botanically these are genera and not species. These common names are mainly unambiguous, but even names such as teak and mahogany can relate to several genera, some of which include species that are protected by regulations under the Convention on International Trade in Endangered Species (CITES) and others not. The use of scientific names is essential. For example, Quercus (oak) and Fraxinus (ash) have very wide geographic distributions in the temperate northern hemisphere and comprise many species (c. 530 and 43, respectively), and pantropical genera such as Dalbergia (rosewood) are often very large (c. 250 species). Not only are these genera widespread, but the woods within each genus look very similar to each other and often to other genera, and many cannot be separated to species level by eye or under the microscope. Trade-in timbers such as ash (Fraxinus) can also be a plant health issue when moved geographically (Spence et al., 2020).

4 | PROVENANCE: WHERE DOES IT COME FROM?

This is usually a more difficult question to answer than the identity of species or genus. Commercial forestry expertise extends across the globe, with the same species being grown in more than one country, often on more than one continent. The products of harvested timber, sawn timber, and logs can be traded to a second country, part processed, and transhipped to a third country where finished products are manufactured before re-exporting to markets in the west. Illegal logging and export of timber are a problem in many countries (EIA, 2012; including Peru), and there is compelling evidence that oak furniture and flooring imported into the USA and Europe often comprises several species of white oak from North America and the Russian Far East (EIA, 2013). It cannot be assumed that products made in a country come from trees that grew there.

5 | OUR APPROACH TO ANSWERING THESE TWO QUESTIONS

Scientific methods are needed that will allow the comparison of suspect wood with reference wood samples of precisely known geographic origin and identity. These comparisons will only be possible when there is sufficient reference material (i.e., correctly named wood samples) to meet this need and scientific techniques that are reliable enough to answer the two questions. The passage of all samples from forest to Kew and beyond is being recorded on a smartphone application (https://app.worldforestdid.org/) developed by colleagues at the University of Tennessee. This app, based on TreeSnap (Crocker et al., 2019) has been designed to capture field data including precise location coordinates and fraud prevention measures and meets the chain of custody needs of law enforcement.
5.1 Sampling in forest

A key requirement is to collect samples suitable for any type of wood identification analysis method and to ship them from remote forests under conditions that preclude degradation and the growth of molds. WFID has developed collection protocols for two types of sample: sawn discs obtained from tree trunks during or close to the time of harvest and wood cores obtained from a mechanical device, the “Pickering Punch,” used to bore fresh material from standing trees. The “Pickering Punch” comprises a hardened sharp metal tube that is driven into a tree at waist height. A core $18 \, \text{mm} \times 125 \, \text{mm}$ is collected in the device and transferred to a cardboard storage tube (Figure 1a,b). Versions that extend further into the trunk are being tested. Although a small area of the cambium is damaged in the process (Figure 1c) this is unlikely to do long-term harm and is far less damaging than many of the challenges the tree faces throughout its life (Morris et al., 2020). Three cores are collected from each tree, one for retention in the country and two shipped to Kew once properly dried. The number of species and tree replication is decided for each site and depends on the site’s size and logistical concerns such as the number of personnel available and distance from a base where the samples can be dried and processed. Prioritization of species, locations, and the number of samples per species is based on what is needed for the reference databases plus which species and locations have a higher risk of entering trade illegally based on forest trade data. WFID’s choice of locations based on risk will improve as the program moves forward.

Logistics and moisture control are essential facets of reference sample collection: relevant permissions, export, and import certification requirements are needed, including CITES permits when necessary. Voucher material in the form of leaves in silica gel (for future DNA analysis) and, where possible, herbarium specimens comprising foliage, flowers, and fruits, are also collected. It is required that voucher specimens are obtained directly from the sampled tree and not from foliage found around it. Green timber has a high moisture content (typically >80%) making sample spoilage post-harvest a risk. Moisture is controlled by local drying and the use of rechargeable silica gel pouches that are placed alongside the sample immediately after collection and during shipment to Kew.

Samples are received at Kew’s Plant Quarantine Unit where they are inspected for contamination (i.e., pests and pathogens). All incoming material is frozen at $-40^\circ \text{C}$ for 72 hr to kill any invertebrates that may be present. Only when necessary, samples are autoclaved to kill bacteria, yeasts, and fungi and subsequently put in an incubator to dry. Contaminated packaging is autoclaved prior to disposal. Field collection protocols are constantly being refined to eliminate mold issues caused entirely by inadequate drying prior to shipping. Following processing in Quarantine, the samples are checked for identity using wood anatomy (by PEG, IMB) and morphological examination of foliage, flowers, or fruits (by Kew Herbarium colleagues). Provided there are no identification issues, wood subsamples of the entire collection are cut for shipping to analytical laboratories for further vetting. The methods used, DART-TOFMS and IRMS, efficiently screen the selection for outliers that can then be substantiated by the more time-consuming anatomical methods. By cross-checking the identification results of each method prior to incorporation in the final database, a robust collection is constructed.

6 METHODS USED FOR IDENTIFICATION

These can be broadly separated into observational (macroscopic and microscopic), chemical (various chromatographic, mass spectrometry techniques), and DNA analysis. These are discussed below.

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**FIGURE 1** Four images showing the wood sampling process and Kew’s wood collection. (a) Pickering Punch kit, (b) wood sample core of *Cedrela fissilis* (Meliaceae) with sapwood and heartwood and the storage tube showing the unique barcode and number, (c) healed sampling hole on a *Prunus avium* tree, 18 months after sampling, (d) examining Meliaceae (mahogany) wood samples in the Kew Economic Botany collection (xylarium)
6.1 | Macroscopic examination of solid wood

Macroscopic and microscopic examination are the first steps for the assessment of timber identity. Some woods can be recognized with the naked eye. Many temperate woods such as oak (Quercus), ash (Fraxinus), elm (Ulmus), and beech (Fagus) have characters distinctive enough to be seen by eye or with a hand lens. However, as with microscopy, identification to species level is usually not possible unless assumptions can be made about the precise geographic origin. An identification to genus level may be sufficient but there are numerous examples where this is not the case. The main advantage with this technique is that it is easy and inexpensive to examine material but considerable expertise is needed to interpret characters and to arrive at a correct identification, especially with the multitude of tropical hardwoods and very similar temperate softwoods. Ruffinato et al. (2015) provide guidance on the interpretation of features by eye. Many publications provide macro-photos of worldwide woods, including Illic (1991) and Ruffinatto and Crivellaro (2019). CITES-listed species are treated by Miller and Wiedenhoeft (2002), Richter et al. (2014) and a guide encouraging the use of photos taken with a mobile phone is being published on the internet by Esteban et al. (2020). Attempts to reduce the need for human expertise are being made using automated machine learning (Andrade et al., 2020; He et al., 2020; He et al., 2020; Hermanson et al., 2019; Hermanson & Wiedenhoeft, 2011; Ibrahim et al., 2017; Olschofsky & Kohl, 2020; Paula Filho et al., 2014; Ravindran et al., 2020; Souza et al., 2020; Wang et al., 2013; Yusof et al., 2013). This is clearly a rapidly moving field of study. For automated machine learning to achieve its potential, adequate training datasets are required. Two issues that remain to be solved are the availability of enough reliably identified replicates of wood of a given species taking into account variations in radial growth rate and ensuring that the image analysis programs are not biased from lack of samples.

6.2 | Microscopic examination of thin sections on microscope slides

Microscopic analysis is the traditional method used by most wood anatomists and where many anatomical features can be seen with thin sections that cannot be seen on a solid piece of wood at low magnification (Gasson, 2011; IAWA Committee, 1989, 2004; Koch et al., 2011, 2015). Wood needs to be boiled or at least softened with warm water before thin (15–40 μm) sections are cut using either a microtome or single-sided razorblade. The wood is sectioned in three planes (Transverse Section (TS), Tangential Longitudinal Section (TLS), and Radial Longitudinal Section (RLS)) and compared with reference microscope slides under a compound microscope at magnifications mainly between ×40 and ×400, and less often up to ×1,000 for very fine anatomical features. Even if a good reference microscope slide collection is available, none are comprehensive and online databases and multiple-entry keys should be employed for comparison such as InsideWood (2004) (https://insidewood.lib.ncsu.edu/search), and Richter and Dallwitz (2000).

Microscopy permits the examination of many features that cannot be seen by eye or with a hand lens and some characters are very good at narrowing down the number of possible identities of a piece of wood (IAWA Committee, 1989, 2004). Wheeler et al. (2020) provide a table of the proportion of the 7,371 anatomical descriptions in InsideWood with each anatomical character, and this gives a good indication of which ones have particular diagnostic value singly and in combination. As with macroscopy, expertise is necessary, and machine learning and other neural network methods are being investigated to aid or reduce the need for human expertise in order to improve point-of-contact identification of suspect wood (e.g., Lens et al., 2020; Martins et al., 2013; Silva et al., 2017). These developments do not eliminate the need for expert wood anatomists but provide alternative methods of identification in the current reality of the declining population of expert anatomists despite the increased global trade in wood products.

6.3 | Chemical techniques

Chemometrics include the search for chemicals that are unique or restricted to a particular taxon (see Kite et al., 2010 on Dalbergia nigra) and measurement of chemical profiles using DART-TOFMS. NIRS (Near-Infrared Spectroscopy) is not currently being employed by WFD, but has been used to identify wood (Bergo et al., 2016; Braga et al., 2011; Pastore et al., 2011; Soares et al., 2017) and charcoal (Muñiz et al., 2016) of Swietenia macrophylla (mahogany), Dalbergia species (rosewoods) and various “Angelim” species (Diptropis, Hymenolobium, Parkia, Vatairea) in Brazil.

6.4 | Direct analysis in real-time time-of-flight mass spectrometry

Direct analysis in real-time time-of-flight mass spectrometry (DART-TOFMS) is being used to great effect by the Office of Law Enforcement (OLE) National Fish and Wildlife Forensic Lab (NFWFL; Ashland, OR) and the United States Forest Service International Programs Wood Identification & Screening Center at Oregon State University (WISC; Corvallis, OR) to identify CITES-listed and commercially significant timbers imported into the US. The method is based on chemical fingerprinting of the small molecule profile, or chemotype, of heartwood. The process is shown in Figure 2 for the separation of wood from four morphologically similar genera. Another example is that the chemotypes of anatomically similar Dalbergia species are chemically distinct allowing for discrimination (Lancaster & Espinoza, 2012). NFWFL has developed the Forensic Spectra of Trees Database (ForeST®) comprising of 16,000+ chemical fingerprints capable of identifying wood species. Unlike morphology and anatomy,
where observational expertise is required to interpret reference databases, DART-TOFMS instruments need to be calibrated to ForeST© to take advantage of the existing capabilities due to the complex matrix of wood.

Currently, ForeST© is the only global database capable of identifying all CITES species in addition to 2,000+ other commercial wood species (http://woodid.info/tools/). The methodology employed by both NFWFL and WISC recommends a three-step process for identification that includes ForesST© NIST search, visual inspection of the unknown sample spectra against the reference data, and statistical classification. The full protocol is given in Schmitz et al. (2020). Both laboratories regularly use DART-TOFMS for species classification of suspect timber and in 2018 WISC processed over 132 items for regulatory partners. Many publications have derived from this collection and database, for example, Lancaster and Espinoza (2012), McClure et al. (2015), and Deklerck et al. (2017).

6.5 | Gene sequences—DNA

DNA is most easily extracted from green tissue such as leaves. It can be extracted from the inner bark (i.e., living phloem), the cambium, and the sapwood, especially if the sapwood has plenty of living axial parenchyma or ray tissue, and this will depend on the taxon and its anatomy. DNA is much more difficult to obtain from heartwood, very old timber samples in xylaria and antique furniture (Abe et al., 2011) although there are examples in the literature where this has been done, even with timber from shipwrecks such as the Mary Rose (Speirs et al., 2009). Moreover, relatively few DNA reference datasets exist for the vast number of timber species traded on the global market. Although DNA reference sequences exist for some timber species traded on the global market, these standard DNA barcode markers are not sufficiently variable to identify closely related tropical tree species. More variable markers are costly and time-intensive to develop, and reference libraries for them need to be built. At present, the building of comprehensive wood collections along with material suitable for reference DNA databases—species by species and region by region—continues to be a very expensive, time-consuming undertaking.

Although it may be possible to match DNA sequences from wood with existing known sequences, and thereby identify a genus or species, this will not necessarily pinpoint geographic origin. Lowe and Cross (2011) discuss the various issues and comment that in some cases molecular genetic methods can provide a high degree of precision ranging down from species to the individual. Tectona grandis (Teak), Swietenia macrophylla (Mahogany), and Cedrela odorata (Spanish Cedar) are examples of tropical species
and various eucalypts (Eucalyptus spp.) and poplars (Populus spp.) are temperate species which are grown in plantations well outside their natural geographic ranges. A South American species such as Cedrela odorata grown in Africa will have the same genome as the trees from which it was sourced in South or Central America. Investigations such as those by Paredes-Villanueva et al. (2020) on nuclear and plastid SNP markers in Cedrela timber may ultimately overcome such problems, which can be particularly acute with taxa listed on CITES appendices such as Cedrela and Swietenia where there is scope for claims on origin documents to be falsified, and timber grown outside the native range is exempt. The genetic techniques being used to ascertain identity and provenance are explained in the “GTGN guide for the different timber tracking methods” (Schmitz et al., 2020) which provide references to provenance work on a wide range of temperate and tropical species including the mahoganies Carapa, Cedrela and Entandrophragma cylindricum (Meliaceae), legumes Dipterx and Hymeniaeae, temperate taxa Acer macrophyllum, Fraxinus excelsior, and Larix, and the SE Asian Gonystylus. This may seem like a long list, but very few taxa have been studied compared with the number in international trade. DNA databases currently lag behind wood anatomical databases such as InsideWood and the many publications on wood anatomy which cover the majority of commercial species and the DART-TOFMS Forensic Spectra of Trees Database (ForeST©) which include the chemical signature of every CITES-listed timber species.

7 | METHODS USED FOR PROVENANCE

The most widely used method that can reliably provide information on provenance is stable isotope ratio analysis (SIRA). As discussed above, it has advantages over DNA analysis for provenance, but cannot be used at all for identification.

7.1 | Stable isotope ratio analysis for timber provenance verification

Stable isotope ratio analysis (SIRA) is the technique with the most promise for verifying the provenance of timber. All living organisms sequester elements during their lives, and the stable isotope patterns of H, O, C, N, S, and other elements will differ depending on where the organism lived. It is unlikely that the pattern exhibited by these elements in combination will be the same in distant places. SIRA involves the use of an Isotope Ratio Mass Spectrometer (IRMS), a specialized device developed by Nier (1940), to measure the relative isotopic abundance of elements within a given sample. It is now a widely established analytical discipline, proving popular with scientists wanting to establish the geographic, chemical, and biological origins of organic substances. Since the turn of the century, a growing number of laboratories around the world have adopted the technology as a means of verifying the origin of food and drink (Boner & Förstel, 2004; Heaton et al., 2008; Kelly et al., 2007; Kelly & Rhodes, 2002; Li et al., 2014; Pilgrim et al., 2010). The same principles used to authenticate food were later applied to timber provenance research (Boner et al., 2007; Gori et al., 2013, 2018; Horacek et al., 2009; Kagawa et al., 2008; Kagawa & Leavitt, 2010; Keppler et al., 2007; Rees, 2015). Stable isotope signatures have also been used to assess how environmental and physiological effects define the isotopic composition of C, O, and N in the wood of tropical trees (Sleen et al., 2017).

Verifying the precise geographic origin of timber typically depends on comparing a sample with a claimed origin against an authentic reference database covering the same origin. The technique is used routinely to assess legality, compliance with labeling legislation, validation of claims in forest certification schemes, and its use to conduct due diligence is advocated by EUTR (Regulation (EU) No 995/2010). If enough samples can be obtained from each location of interest the resulting database of stable isotope patterns should mean that claims as to origin can be tested and either confirmed or refuted. In many cases, the latter is more likely. If the pattern does not match that of a claimed origin (labeling claim), then there is a high probability that the sample in question was harvested elsewhere. Stable isotope databases are rapidly being built on a range of commercial timbers from both temperate and tropical areas. Agroisolab have provided stable isotope evidence for investigations by FSC since 2015, UK enforcement since 2016, and for US enforcement since 2018. One paper has been published on isoscapes of North American oaks (Quercus, Watkinson et al., 2020) and reports on Gabonese and Solomon Islands samples will soon be available on the WFID website.

The samples collected by WFID will provide abundant material for research on stable isotope signatures. This includes investigating how good the geographic resolution is for a particular species and whether adjacent tree species with different phenologies sequester stable isotopes in the same proportions. Ultimately, WFID consortium partners would like to be able to tell precisely where a tree grew and whether a piece of timber came from the concession it is said to come from, or from an adjacent protected area such as a national park. Once the WFID xylarium is fully established the consortium partners will be in a stronger position to answer such questions.

8 | FUTURE-PROOFING REFERENCE COLLECTIONS—WorldForest ID

To ensure that wood reference samples are suitable for all current and future techniques, well-preserved and curated, uncontaminated, reliably identified, and accurately provenanced wood samples are needed in our xylaria. The aim of the WFID program is that specimens collected from now on will meet all these requirements. A particular need is that all the geographic provenance information is accurate and cannot be interfered with. We are aware that samples could be supplied with fraudulent geo-locations in an attempt to mislead, by, for example, stating that timber comes from a concession
rather than a nearby protected area. For this reason, a high level of security will be needed to access full details of each tree collected, and WFID collectors will be unable to change or delete information that was automatically captured by the WFID smartphone app at the time of collection. We are currently obtaining our samples from trusted FSC concessions and will have rigorous selection criteria for future providers of wood samples. All field expeditions have included a WFID Advisory Board member who provides the training for and supervision of field crews. As WFID grows the number of trusted partners will increase.

The WFID smartphone application (https://app.worldforestid.org/) is being used to record the precise geographic location of

**FIGURE 3** Geographic locations of trees collected for WFID from Peru. The yellow spots show the number of trees collected in that location. Clicking on the spot will lead to individual tree data. The detail available will depend on the user’s level of access
each tree, photos of the tree, its identity, and details of the extent of “voucher” material (leaves in silica for future DNA sequencing and enough material to be verified/identified by a herbarium taxonomist). Figure 3 shows the locations of trees collected in Peru. The app is being developed at the University of Tennessee, and has multiple features aimed to prevent and detect fraud such as timestamps and GPS coordinates that cannot be overridden. It enables WFID to follow the precise origin and route of the collected samples within the country and their passage to Kew, to check the information supplied and record further movements of subsamples to laboratories for analysis, with further links to the data derived from them. This will be a great advance on the usefulness of the resulting wood collection (xylarium) in comparison with most xylaria currently available (Index Xylariorum IV). The xylarium at Kew has c. 50,000 reliably named referenced wood samples. The latter and the thousands of microscope slides derived from them and other xylaria are perfectly suitable as reference material for wood identification and for demonstration purposes, but only a small proportion have detailed information on the country/region of harvesting and relatively few are associated with herbarium voucher specimens allowing dubious samples to be checked (see Goodwin et al., 2015). For example, in the Jodrell Laboratory there is a range of teak (Tectona grandis) wood samples which vary enormously in color and density, all with country of origin but no further indication of provenance. Whereas these teak samples, all of one species, look very different from each other, various mahoganies such as Swietenia, Entandrophragma, and Khaya look so similar to each other that it would be very unwise to pronounce on their identity just by visual examination (White & Gasson, 2008).

8.1 | Reconciling the requirements of legislation and what science can provide

Legislation requires yes/no black or white answers. Biological science can rarely provide such unequivocal results. Plants are given scientific names by taxonomists who often differ in their opinions and their classifications of related taxa. A knowledge of nomenclature and scientific names is beyond the interest of many timber users but does go some way in explaining why there are so many discrepancies between botanical nomenclature and names used by industry. The situation is compounded with common/local/vernacular names where the same name can be used for several often botanically unrelated taxa or many different names are used for the same species. Timber and timber products in trade are accompanied by documents stating the identity of the woods involved, but these are often inaccurate, either inadvertently or deliberately. Unraveling common names and matching them to scientific names can be complicated, but resources such as woodid.info and Miller & Ilic (common name database online) will often help if searched with care in the context of the information available. Another complicating issue is that timber products such as furniture often consist of several different woods manufactured in one place but with different geographic origins. The inescapable solution is that the documents associated with timber and its products must use scientific names because common or trade names are too imprecise and open to misinterpretation.

9 | CONCLUSIONS

Ascertaining the identity and provenance of woods in trade can be challenging and is increasingly required in efforts to monitor, regulate, and enforce laws governing the international timber trade. In addition to global policy changes for more transparent supply chains, the best way forward is to build comprehensive collections of reliably identified vouchered wood samples of the relevant timber species with known precise provenance, and to submit these samples to observational and chemical analysis, producing reference data that can be used for comparison with traded timber. Cross-disciplinary research is undergoing that focuses on complementary identification methods rather than competition between them. A combination of two or three techniques, including anatomy, stable isotope ratio analysis, and DART-TOFMS will provide the answers much better than one technique alone, and they can be used to test the accuracy of permits accompanying timber shipments. A prerequisite for all samples in the reference xylarium is that they have been received from trusted sources, are accurately named and reliably geo-referenced for provenance. Ultimately, when reference collections of traded taxa are sufficiently comprehensive it will be possible to assess the accuracy of claims of any shipment of timber, raw, or manufactured.

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AUTHOR’S CONTRIBUTION

All authors are active participants in WFID, responsible for various aspects of the program described in this paper. PEG conceived and coordinated his co-authors contributions as follows: Ry, RPG, MPF, PEG, and ETL on the organization and aims of WFID, SR, IAMB, PEG, RPG, and Ry on the stages between field to Kew and beyond, PEG on anatomy, CAL on chemistry, Ry and GR on SIRA, and PEG and MPF on genetics.

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