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Interpretation and implementation of the Convention

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TIMBER IDENTIFICATION

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Discussion

Forensic timber identification: It's time to integrate disciplines to combat illegal logging

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ABSTRACT

The prosecution of illegal logging crimes is hampered by a lack of available forensic timber identification tools, both for screening of suspect material and definitive identification of illegally sourced wood. Reputable timber traders are also struggling to police their own supply chains and comply with the growing requirement for due diligence with respect to timber origins and legality. A range of scientific methods have been developed independently with the potential to provide the required identification information, but little attention has been given to how these tools can be applied synergistically to support the legal timber trade. Here we review the use of visual identification methods (wood anatomy, dendrochronology), chemical methods (mass spectrometry, near infrared spectroscopy, stable isotopes, radio-carbon), and genetic methods (DNA barcoding, population genetics/phylogeography, DNA fingerprinting) each with potential application to forensic timber identification. We further highlight where future research and development are required to identify illegal logging crimes using these methods and suggest ways in which multiple methods can be used together to answer specific identification questions. We argue that a new integrated field of forensic timber identification should be a global investment priority, for which the ongoing collection, curation and taxonomic study of appropriate reference material is a critical part. Consideration of the specific legal requirements for method development and the application of identification methodologies to criminal evidence are also imperative to achieve robust scientific support for illegal logging crime prosecutions and prevention.

1. Introduction

Deforestation represents a massive threat to global biodiversity with illegal logging and the associated trade in illegally sourced wood products a significant contributor to the continuation of unsustainable deforestation rates. International efforts to combat the problem consist primarily of the enactment of laws designed to discourage the trade in illegally sourced timber, and prohibit or limit the trade of specific species or those from specific areas. Trade

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restrictions are imposed primarily through the Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES) which lists species in one of three appendices depending on the degree of protection required. Appendix I is the most restrictive and prohibits trade in taxa threatened with extinction, trade is only permitted in exceptional circumstances; Appendix II lists species which are not currently at threat of extinction, but require controlled trade to avoid over-utilisation and future extinction threats; Appendix III lists species that are controlled in at least one country which requests assistance in trade control from other signatory countries. In addition to CITES, consumer countries increasingly prohibit the importation of any timber not obtained in accordance with the laws of the country of origin, e.g. Canadian Wild Animal and Plant Protection and Regulation of International and Interprovincial Trade Act (1992); US Lacey Act (amended 2008); EU Timber Regulation (2010); and Australian Illegal Logging Prohibition Act (2012).

Abraham Lincoln once said “Law without enforcement is just good advice” and currently this is the status quo in most parts of the world with regards to illegal logging legislation. With the best of intentions, law makers have set enforcement officers an impossible task; to seize illegal wood products and prosecute illegal logging crimes, without in most cases the means to identify timber to a level of certainty acceptable for admission to a court of law. The push for more sustainable forestry practises also comes from within the industry, with reputable traders eager to comply with new laws, but similarly facing the daunting task of policing their own supply chains without the scientific tools to independently verify the origin of their wood products. One of the key problems is that timber products do not generally possess the diagnostic features required for plant identification (i.e. the leaves, flowers and fruits of the tree) and hence reliable identification is extremely challenging. Identification questions most often begin with the taxonomic identity of a product (i.e. from which genera or species does the timber originate?). Questions of geographic region of origin often follow as some species are only trade-restricted from certain areas of their distributional range but not others (e.g. some species listed in CITES Appendix III). In this context, ‘region’ refers to a specific geographic area, which may or may not be synonymous with a country or recognised subdivision within. The age of a specimen can also be important, as timber harvested prior to legislation is often exempt. Finally individual identification is sometimes sought, to link timber products to the original tree, either as part of supply chain verification systems or to identify theft.

Table 1
Screening methodologies for forensic timber identification.

	Macroscopic wood anatomy	Microscopic wood anatomy	Machine vision	Near infrared spectroscopy	Detector dogs
Identify genus	Yes	Yes	Yes	Yes – depending on suite of taxa used to train the model	No
Identify species	Occasionally	Occasionally	Occasionally	Yes – depending on suite of taxa used to train the model	Yes
Approximate cost per sample for screening	<$1 USD – cost for knife blades	<$100 – cost for making slides and professional wood anatomical expertise	<$1 – identifications are achieved at the cost of the power to operate the machine	<$1 – identifications are achieved at the cost of the power to operate the machine	<$10 – cost of maintaining a dog
Speed of initial ID	Minutes to hours (depending on experience)	Days (if sending to external wood anatomy lab)	Minutes	Minutes	Minutes
Equipment requirements for application as screening tool	Knife, hand lens	Microscopy preparation and observation tools	Machine vision camera and database link	NIRS machinery and database link	Dog and handler
Training requirements for use as screening tool	Extensive and ongoing in order to be reliable. Front line staff can obtain proficiency	Extensive and ongoing, only professional wood anatomists can perform reliably	Minimal, only initial training on operation, maintenance and updating required	Minimal, only initial training on operation, maintenance and updating required	Dog requires extensive training (many months)
Reference material requirements	Electronic databases, ID guides	Access to microscopic wood anatomy examples through microscope slides and electronic databases	Central database loading of microscopic wood anatomy examples from wood specimens	Regional specific database loading of reference spectra obtained from wood specimens	Examples of wood specimens from the desired suite of taxa plus lookalikes
Development potential as screening tool	Fair – easiest method to provide materials for, but has the greatest risk of failure to provide correct identification when employed by non-expert	Poor – most reliable method to provide initial identification but number of trained anatomists very low, and training can take decades	Excellent – if fully functional could provide fast and accurate IDs for law enforcement	Good – if fully functional could provide fast and accurate IDs for law enforcement; must be pre-loaded with region specific species data.	Good – number of species limited by dog capacity; could be added to remit of other contraband detector dogs
Current use as screening tool	Only method in general use	Currently used by some major customs organisations.	Not currently used beyond pilot studies	Not currently used beyond pilot studies	Currently used in pilot studies and by some major customs organisations
Obstacles to implementation as screening tool	Delivery of accessible training materials and high staff turnover on the front line	Low numbers of trained wood anatomists and difficulties with accessing their services	Production and roll out of equipment and incorporation of reference material into database	Cost of equipment and incorporation of reference material into regional specific databases	Access to reference material and training programmes
Research needs for application as screening tool	Analysis of effectiveness of current training provisions, new models for training delivery	Discrimination between closely related taxa, new models of access to expertise e.g. remote provision identification using high quality microscopic photography	Analysis of effectiveness in identification of larger suite of taxa, usability in front-line context	Analysis of effectiveness in identification of larger suite of taxa, usability in front-line context	Assessment of potential to discriminate regional differences within taxa, development of training guide

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Table 2
Diagnostic methodologies for forensic timber identification.

	Wood anatomy	Machine vision	Dendro-chronology	Mass spectrometry	Near infrared spectroscopy	Stable isotopes	Radio-carbon	DNA barcoding	Population genetics/phylogeography	DNA fingerprinting
Identify genus	Yes	Yes	No	Yes	Yes	No	No	Yes	No	No
Identify species	Occasionally	Occasionally	No	Yes	Yes	No	No	Yes	Occasionally	No
Identify provenance	Occasionally	Unknown	Occasionally	Yes	Yes	Yes	No	Occasionally	Yes	No
Identify individuals	No	No	Yes	No	No	No	No	No	No	Yes
Determine age	No	No	Yes – where growth rings are present	No	No	No	Yes	No	No	No
Approximate cost per sample including expertise	<$100	<$1	<$100	<$1–$100 – depending on the mass spectrometry method used	<$100	$100–400	$300–400	$100–$300	$100–$300	$100–$300
Speed of process	Minutes–days	Seconds–minutes	Hours–days	Minutes–days depending on the mass spectrometry method used	Seconds–minutes	Several days	Several days	Several days	Several days	Several days
Prior information requirements	None – but suspected region of origin can be helpful	None – but suspected region of origin can be helpful	species	Suspected genus	Broad region of origin	Species	None	None – but suspected taxa can be helpful	Genus for species ID, species for regional ID	Species
Equipment requirements	Microscopy preparation and observation tools	Machine vision camera and database link	Macroscopy equipment	Mass spectrometer and equipment for isolating extractives (if required)	Near infrared spectroscopy machinery and database link	Light gas isotope ratio mass spectrometer and elemental analyser	Liquid scintillation counting and accelerator mass spectrometry equipment	Molecular biology laboratory	Molecular biology laboratory	Molecular biology laboratory
Reference material requirements	Access to microscopic wood anatomy examples through microscope slides and electronic databases	Central database of scientific reference images processed for automated classification	Tree ring series data derived from reference tree cross-sections from specific areas	Heartwood samples from multiple individuals of the desired taxa and potential lookalikes	Regional specific database loading of reference spectra obtained from wood specimens	Wood samples from the desired species with various tree rings	None	Leaf, cambium or wood samples from the desired taxa and potential lookalikes	Leaf, cambium or wood samples from multiple individuals from across the range of the species	Leaf, cambium or wood samples from multiple individuals from across the range of the species
Current use	The most commonly and extensively used method for genus ID	Used predominantly in a research context and in pilot implementation projects	Used occasionally to match wood coming from same tree or to determine antique verses modern origin of timber	Used extensively for identification of some taxa (e.g. *Dalbergia*)	Used extensively for assessment of wood properties Currently used in pilot studies for identification	Used extensively for origin check in agricultural products and used in proof of concept studies and pilot tests for timber	Used extensively for age determination in a wide range of materials, limited application to timber at present	Used extensively for species identification in a wide range of taxa, limited application to wood at present	Used predominantly in a research context and in pilot implementation projects	Used extensively for individual identification in humans and other taxa, limited application to wood at present
Obstacles to implementation	Training of sufficient numbers of wood anatomists, maintenance of reference collections	Incorporation of reference material into database, classification models robust for global context vs. regional models	Collection of tree ring series data for important taxa in areas of interest	Development of reference databases for additional taxa of interest	Development of reference databases for additional taxa of interest	Development of reference databases for additional taxa/areas of interest	No significant obstacles to implementation	Development of discriminating barcodes that work on DNA extracted from wood	Development of genetic markers and reference databases that discriminate areas and taxa of interest	Development of genetic markers and reference databases that discriminate individuals in taxa of interest
Research needs	Discrimination between closely related taxa, forensic validation of methods	Development of global scientific image reference collection, uncertainty quantification and probabilistic model development	Accuracy of dating, provenancing and individual ID, forensic validation of methods	Forensic validation of methods for additional taxa	Development of reference databases, forensic validation of methods	Development of reference databases, forensic validation of methods	No specific research needs with regards to timber	Development and forensic validation of DNA barcoding methods	Development and forensic validation of discriminating genetic markers and reference databases	Development and forensic validation of discriminating genetic markers and reference databases

Several separate scientific disciplines have turned their attention to the problem of timber identification (Tables 1 and 2); the most established of these is the study of wood anatomy — which provides taxonomic characterisation based on the internal structure of timbers. Other identification methods include various forms of visual, chemical and genetic analysis. However, these methods vary quite considerably in terms of the granularity of identification that is afforded, which is also dependent on taxonomic group. In addition, the prior information required and the cost of analysis also varies widely (Tables 1 and 2). Due to the disparate nature of the various disciplines, and the relative infancy of many of the specific identification techniques, there has been very little synthetic work to date which seeks to assess the current state of the art (but see Wiedenhoeft and Baas, 2011).

Methods for tracking timber based on non-inherent features of wood are currently the most commonly used and can provide complementary information to assist with illegal timber investigations. These methods include simple measures such as the use of painted identification marks and paper based certificates but also range to more sophisticated measures that present significant problems for those seeking to commit fraud, such as the use of physical barcoding tagging systems and radio frequency identification (RFID) tags (Seidel et al., 2012). However, for forensic diagnostic timber identification, only those methods which rely only on inherent wood characteristics (such as anatomy, chemistry and genetics) can provide reliable identification outcomes to support the law; it is these specific methodologies that are the subject of the current paper.

Here we review the various scientific methodologies that have potential for use as forensic timber identification tools and consider how multiple approaches could be integrated to answer a range of identification questions. Our treatment of each approach is necessarily brief, but intended to provide an overview and direct the reader to more in-depth material where desired. We also explore some of the issues pertinent to all identification methods, such as the availability and taxonomic integrity of reference material, and the steps required to take academic research into the forensic arena.

Timber identification was historically a branch of wood technology, but is now generally considered to be part of the broad fields of wildlife forensics and forensic botany. However, wildlife forensics focuses almost exclusively on animals, and forensic botany on the use of plant identification to solve crimes, usually where traces of plant material are found at the scene of a crime and can be used to link back to the perpetrators. Forensic botany rarely focusses on illegal logging, in which the trees themselves are the victims of criminal activity. This gap between policy requirement and scientific application has been highlighted by a recently convened expert working group on the subject, brought together by the United Nations Office of Drugs and Crime (UNODC). Given the scale of illegal logging and urgent need for practical timber identification solutions, we contend that the interdisciplinary field of forensic timber identification should be established as a specific research and investment priority.

2. Science for timber identification

2.1. Visual methods

2.1.1. Wood anatomy

Timber identification has traditionally been provided by wood anatomists through the examination of the internal structure of wood (see Carlquist, 2001 and references therein for information on the history of wood anatomy as a discipline). As anatomical characters can be influenced by both genetic and environmental factors, combinations of characters can be used to differentiate taxa. Standard anatomical characters are described according to the terminology of the International Association of Wood Anatomists (Richter et al., 2004; Ruffinatto et al., 2015; Wheeler et al., 1989) and identification obtained through comparison to reference materials. Analysis can be undertaken at both the macroscopic and microscopic scale, but microscopic examination is usually required to achieve a diagnostic identification. Wood anatomical analysis can generally only achieve identification to the genus level (Gasson, 2011). Automated wood anatomical analysis ('machine vision') through the use of sophisticated image capture and processing algorithms is a new area of research showing much promise for timber identification (Hermanson and Wiedenhoeft, 2011), and could potentially facilitate identification to the species level in some cases, thanks to the system's sensitivity to variations that are not easily observable or interpretable to the human eye. However, in order for the system to achieve such discriminatory power, reference material requires integration into the image database such that the natural variations in wood structure of specific taxa are captured. A concerted global effort to incorporate images of the world's xylaria would dramatically improve the system's utility.

Wood anatomical analysis is the most frequently used method for taxonomic identification, both on the front-line for screening purposes, and in the laboratory for diagnostic identification. Screening is most commonly undertaken by front-line officers themselves, with the assistance of various identification aides which describe the macroscopic structure of specific timbers that can be observed with basic magnification (i.e. a hand lens). These materials typically take the form of posters (e.g. Groves, 2003; White et al., 2003a,b), manuals (e.g. Miller and Wiedenhoeft, 2002; Wiedenhoeft, 2011) and interactive databases (e.g. Coradin et al., 2010; Koch et al., 2011; Richter et al., 2002). Machine vision of anatomical features also potentially offers excellent prospects as an automated tool that could be used for screening purposes, but currently requires additional investment, research and development before being a realistic option for front-line law enforcement (Table 1).

2.1.2. Dendrochronology

The science of dendrochronology is another visual method with the potential for use in forensic timber identification. Dendrochronology focuses on the study of periodic growth rings laid down by (predominantly temperate) tree species. Individual rings contain information on the environment at the time of growth and the sequence of rings can provide a valuable record of the conditions at the time. Dendrochronology is typically applied to elucidate past climates but also has the potential provide an age and provenance of trees (Speer, 2010). The ability to correctly assign provenance using dendrochronology is probably limited, although it has been successfully used to identify the origins of archaeologically important timbers (Haneca et al., 2005). The approximate felling date of a tree can potentially be determined if timber products possess the outer most growth rings and bark (e.g. Wolodarsky-Franke and Lara, 2005; Yaman and Akkemik, 2009), but error margins can be substantial and therefore problematic (Jones and Daniels, 2012). Individual identification is also a possibility, as growth rings can be 'matched' where they line up between pieces of wood from the same individual, although how consistent these patterns are across the entire trunk length of a tree is as yet unclear. Visual dendrochronological analyses are occasionally applied to forensic timber identification and we suggest further research into their potential utility be undertaken. However, given that the majority of illegally logged timber originates from tropical areas, where distinct growth rings are rare, dendrochronology is likely to have limited application globally. Chemical dendrochronological analyses can also provide valuable information, and are considered in Section 2.2.4.

2.2. Chemical methods

Analyses of wood chemistry can in many cases provide information on timber identification that cannot otherwise be determined by visual means. Trees and other plants synthesise compounds termed phytochemicals that are often specific to their species or higher taxonomic groups (e.g. Julkunen-Tiitto, 1989; Venkatar, 1972). Recent work has shown that intra-specific variation can also be detected in some species by some chemical analyses (Espinoza et al., 2014). Specific isotopes incorporated into phytochemicals can also give information on plant provenance and age (e.g. Krüger et al., 2014; Rummel et al., 2010).

2.2.1. Mass spectrometry

Assessment of phytochemicals laid down in heartwood can be undertaken using mass spectrometry and statistical analyses of the resulting chemical profiles. Depending on natural variation present in the various taxa assessed, and the relative degree of chemical change over time with wood processing and use, identification to a range of taxonomic levels may be possible and have been illustrated in several recent publications focusing on timber analysis. For example, Cabral et al. (2012) used venturi easy ambient sonic spray ionization mass spectrometry (V-EASI-MS) to distinguish *Swietenia macrophylla* from six other visually similar but taxonomically distant timber species. Within the genus *Dalbergia*, Kite et al. (2010) used liquid chromatography mass spectrometry (LC–MS) to distinguish the CITES listed *Dalbergia nigra* from 15 other congeners, and similarly Lancaster and Espinoza (2012a) and Espinoza et al. (2015) used direct analysis in real time and time-of-flight mass spectrometry (DART–TOFMS) to distinguish between 12 *Dalbergia* species and eight lookalike species. Most recently, McClure et al. (2015) were able to successfully distinguish Madagascan *Dalbergia* from African and Asian *Dalbergia*. Other work using the DART–TOFMS system has successfully distinguished between two oak species (Cody et al., 2012), and between *Aquilaria* species and 25 other fragrant woods (Lancaster and Espinoza, 2012b).

Phytochemical analysis using mass spectrometry methods presents an excellent option for future routine forensic timber identification. Results can be obtained quickly and, excluding initial equipment costs, cheaply. Presently there are only a handful of taxa for which the necessary method development has been undertaken, and we suggest that increasing this number should be an urgent priority.

2.2.2. Near infrared spectroscopy

Phytochemical properties can also be assessed using near infrared spectroscopy (NIRS) which characterises wood absorption spectra when exposed to near infrared electromagnetic energy. NIRS is used extensively for wood property elucidation, but much less frequently for taxonomic identification (see Tsuchikawa, 2007; Tsuchikawa and Schwanninger, 2013 for reviews). For timber identification, NIRS has been capable of discriminating between species of different genera (Braga et al., 2011; Pastore et al., 2011; Russ et al., 2009), congenerics of the genus *Quercus* (Adedipe et al., 2008), and between different geographic provenances of *Picea abies* (Sandak et al., 2011). The relative simplicity of the required machinery and speed of use makes NIRS technology another excellent option for screening tools, but further research and development are required, particularly to build up chemical profile databases and the statistical methods that can be applied to classify taxonomic differences.

2.2.3. Detector dogs

Another option for phytochemical screening is via the use of detector dogs trained in the specific identification of particular timber species. Dogs are able to positively identify the scents of various illicit materials and are commonly used to screen shipments for drugs, explosives and other contraband. In 2010, a pilot project was initiated to assess the feasibility of training detector dogs to identify specific timbers. The team were able to successfully train two dogs to detect bigleaf mahogany and Brazilian rosewood and distinguish them from other similar timbers. The dogs achieved a 90% success rate after five months training (Braun, 2013).

2.2.4. Stable isotopes

Analysis of stable isotopes within timber can inform on geographic provenance identification. As phytochemicals are synthesised, they incorporate specific stable isotopes relative to their availability in the surrounding environment, and this in turn is influenced by various factors related to climate and geology. By utilising one or more informative stable isotopes, commonly including the bioelements (carbon, hydrogen, oxygen, nitrogen) (Fry, 2007) and other elements such as sulphur (Thode, 1991) and strontium (Capo et al., 1998; Rummel et al., 2010; Voerkelius et al., 2010), an isotopic signature of a given area can be determined.

The application of stable isotope analyses to forensic timber identification has been reported in a number of high profile ‘grey literature’ publications. In 2010, documentation resulting from an international conference on genetic and isotopic fingerprinting methods was published (Gesellschaft für Internationale Zusammenarbeit), looking at stable isotope analyses in *Tectona grandis*, three species of *Swietenia*, *Entandrophragma cylindricum* and *Milicia excelsa*. In 2011 WWF published a project report giving further details of the ability of stable isotopes to distinguish geographic regions of *T. grandis* and *Swietenia* (Förstel et al., 2011). In 2013, the Environmental Investigation Agency reported on their investigation into illegal logging of oak, ash, linden and elm hardwood from the Russian Far East, where stable isotope analysis was used to determine the origin of wood being prepared for export to US and EU markets. In the peer reviewed scientific literature, Horacek et al. (2009) described the use of stable isotopes to successfully distinguish Siberian from European larch, and Kagawa and Leavitt (2010) achieved extremely fine spatial resolution when provenancing pinyon pines in the south-western United States using carbon isotopes from multiple tree rings in conjunction with dendrochronological data (see Section 2.1.2). Stable isotope analysis is generally gaining momentum as an established forensic tool, particularly in the food and drinks sector (Meier-Augenstein, 2011), and timber identification can benefit from its broader utility to provenance questions.

2.2.5. Radiocarbon

As well as occurring in various stable isotopic forms, carbon also exists as radioactive ^{14}C, otherwise known as radiocarbon, with a half-life of 5730 ± 40 years (Godwin, 1962). ^{14}C decays naturally to ^{14}N, a stable isotope of nitrogen. Formation of ^{14}C occurs predominantly in the upper atmosphere through natural processes and after oxidation to CO_2, ^{14}C is mixed throughout the earth's various carbon pools. Carbon sequestered by plants is fixed from atmospheric CO_2 via photosynthesis, and at that point ceases to be exchanged with the environment and decays predictably to ^{14}N. By measuring the ratio of ^{14}C to ^{12}C, correcting for mass dependent fractionation and comparing to known standards, the radiocarbon age of organic material can be calculated (Ramsey, 2008). Radiocarbon ages have been converted into calendar ages based on data sets derived from independently dated tree ring and marine samples (McCormac et al., 2004; Reimer et al., 2004). In the early 1960s the levels of ^{14}C in the atmosphere were substantially increased due to nuclear bomb testing creating the ‘bomb curve’ in ^{14}C calibrations (Hua, 2009; Hua et al., 2013), and allowing radiocarbon dating of modern samples to within a few years (Currie, 2004). Radiocarbon dating can be used as a forensic timber identification method to determine the age of timber samples when applicability of legislation may be in doubt and is being used increasingly for forensic purposes (Uno et al., 2013; Zoppi et al., 2004). For example, CITES legislation is primarily concerned with timber that enters trade after the listing of particular species. Radiocarbon analysis can determine whether a tree was felled prior to or after the implementation of legislation, although this can be challenging when the outer growth rings of a tree are absent in the timber sample and the date of timber harvest is close to the date of legislation implementation.

2.3. Genetic methods

Analysis of the genetic code of tree species allows assignment of individuals to different groups based on shared ancestry or the relative frequency of different genes. As the genetic code is inherited, individuals with more recent shared ancestry are more similar genetically, compared with more distantly related individuals. Genetic analysis can provide species level identification (or higher taxonomic groups such as genera and families), most commonly achieved through DNA barcoding approaches. Geographic region of origin identification within species can be determined using population genetics or phylogeographic analyses, and individual level determinations can be made using DNA fingerprinting (Lowe and Cross, 2011).

2.3.1. DNA barcoding

DNA barcoding seeks to identify the species of an individual based on variation at specific gene regions (Hebert et al., 2003). In animals, the mitochondrial cytochrome oxidase (CO1) gene region has been adopted as the global standard. In plants, two chloroplast gene regions maturase K (*mat*K) and ribulose-bisphosphate carboxylase (*rbc*L) are currently used as standard, but can only distinguish ~70% of plants, and usually require analysis of additional local barcode regions for species level identification (CBOL Plant Working Group, 2009). The potential application of DNA barcoding for timber identification has been demonstrated using the Internal transcribed spacer (ITS) gene region in the mahogany family (Muellner et al., 2011). CITES listed *Aquilaria* species have also been distinguished from other closely related species using a combination of ITS1 and the *trn*L-*trn*F intergenic spacer (Jiao et al., 2014). A large study aiming to develop a reference library of the Indian tropical evergreen forests successfully assigned sapwood samples to the correct species using the standard barcoding markers (Nithaniyal et al., 2014).

One of the greatest challenges of DNA barcoding in timber is that DNA extracted from wood is generally of poor quality, and it is often not possible to sequence the large fragments associated with the standard barcoding regions, meaning that shorter informative regions need to be developed to attain successful identification via DNA barcoding. In a recent study, (Jiao et al., in press) demonstrated successful extraction of DNA from wood up to 80 years old, but with a corresponding reduction over time in the length of the DNA barcoding regions that could be successfully amplified. DNA barcoding has been criticised in the past for seeking to circumvent the need for basic taxonomy when used for species discovery, however its use in specimen identification is widely accepted (Will et al., 2005). Successful identification outcomes via DNA barcoding are more limited when applied to taxonomically understudied clades containing closely related species (Meyer and Paulay, 2005), and is likely due to problems associated with accurately determining the levels of sequence variation within and between species. The utility of DNA barcoding for forensic identification purposes is gaining recognition and is expected to continue to rise in popularity as capabilities increase and costs of sequencing come down (Iyengar, 2014; Linacre and Tobe, 2011). The existence of extensive online sequences databases add to the future utility of this method for forensic timber identification, such as the Barcode of Life initiative (Ratnasingham and Hebert, 2007) whose BOLD database at the time of writing contains over 58,000 species with barcode sequences from the conifers and angiosperms (both woody any non-woody).

2.3.2. Population genetics and phylogeography

Population genetics and phylogeographic approaches can be used to determine the geographic provenance of individual trees (i.e. differentiation between regions or populations within a species), based on the existence of spatial genetic structure within natural populations, which can usually be found at both local and regional scales (Degen et al., 2001; Hardy et al., 2006). Spatial genetic structure describes the natural phenomenon whereby more proximate individuals of a species are more closely related genetically to one another than individuals further away. By screening multiple individuals from across the range of a species with suitable genetic markers, genographic maps can be developed which can be used to assign unknown individuals back to their area of origin (Deguilloux et al., 2003, 2004; Dutech et al., 2003; Lowe et al., 2004; Petit et al., 1997). The same principal can be used to assign individuals to their correct species group or to identify hybrids (Duminil et al., 2006; Neophytou, 2014), something which can be important in law as hybrids are often exempt from legislation.

Degen et al. (2013) successfully assigned unknown samples of *S. macrophylla* to their country of origin using population genetic approaches and similarly positive results were achieved for geographic regional assignment of *Neobalanocarpus heimii* in Peninsular Malaysia (Tnah et al., 2010, 2009). Successful assignment to relatively small concessional level areas (tens of kilometres) has also been demonstrated in *E. cylindricum* (Jolivet and Degen, 2012). DNA analysis for population genetics and phylogeography is similarly affected by low DNA quality and analyses typically experience a significant drop in amplification success when used with DNA extracted from timber (e.g. Degen et al., 2013; Jolivet and Degen, 2012).

2.3.3. DNA fingerprinting

DNA fingerprinting, otherwise known as individualisation, is the main application of genetic methods to human forensic work (Jobling and Gill, 2004), and uses genetic markers that vary between individuals but show low differentiation between populations (Budowle and van Daal, 2008). By comparing an individual DNA fingerprint to a large enough representative reference sample database, it is possible to calculate the likelihood of an identical profile being generated from an unrelated individual. These probabilities are usually extremely small, leading to the general acceptance of DNA fingerprinting as high quality forensic evidence. Microsatellites are typically used in human and animal forensic cases but often produce poor amplification success in DNA from timber. Single nucleotide polymorphisms (SNPs) are a viable alternative for use with degraded material (Boonyarit et al., 2014). DNA fingerprinting can be complicated in plants due to the occurrence of polyploidy (Masterson, 1994), which makes result interpretation more complex.

DNA fingerprinting could, in principal, be used to link seized wood material back to the stumps of illegally felled trees, although this application is yet to be reported in the scientific literature. Of greater potential utility perhaps, this technology can be used to verify intact chain of custody for routine trade, by matching samples taken at different points in the supply chain. This principal has been demonstrated by Lowe et al. (2010) for *Intsia palembanica* in Indonesia and similar services are beginning to be offered by commercial supply chain consultancies, enabling timber traders to verify the integrity of their own supply chains. This capacity is the major strength of DNA fingerprinting, as it is the only forensic timber identification technology with the potential to independently trace timber products as they travel along the often convoluted global supply network that characterises the modern timber industry. If more products were routinely and reliably traced from their point of origin, most of the subsequent timber identification requirements would be circumvented (Gasson, 2011).

3. Synthesis

3.1. Integrating methodologies

No one scientific methodology is capable of addressing all diagnostic forensic timber identification questions (Table 2). The only option for a functioning forensic timber identification system is to combine methodologies where required, to achieve the desired identification outcome. How to develop such a system, given the disparate nature of the methods and their availability, presents a significant challenge requiring high level international collaboration and coordination, as well as substantial financial support. The majority of timber producing countries, where law enforcement (and therefore timber identification) needs are greatest, are developing nations without the resources to tackle these issues independently.

Most diagnostic methods aside from wood anatomical analysis require identification to at least the genus level before suitable parameters

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for the various tests can be selected, and even in cases where this is not strictly required scientifically (e.g. radiocarbon dating, Section 2.2.5, Table 2) the genus and species level identification will still usually be required information to assess whether a specific law has been broken. The great strength and utility of identification via wood anatomy is that completely unknown samples can be quickly identified to the genus level, facilitating further analysis downstream to achieve additional identification information in a way that is faster and cheaper than any other method that can identify genus (Table 2).

In order to develop the specific diagnostic forensic questions, the following five identification options should be considered in turn: Genus; species; geographic region of origin; age; individual. During forensic question determination, law enforcement should consider which options apply to their specific identification requirements. Genus level identification should always be the required starting point and the further options of species, geographic region of origin, age, or individual can be then be selected as required. Once a set of hierarchical forensic questions have been defined, appropriate methodologies capable of answering the various questions can be assessed for availability and suitability of the specific tests required (Table 2). Where multiple methods can address the same question, it may be possible to improve accuracy by utilising both. For example, samples of *M. excelsa* and *E. cylindricum* species from Cameroon were mapped simultaneously using both stable isotope and population genetic approaches. Combined results correctly identified whether ~94% of blind samples came from their declared provenance, a success rate greater than that achieved by either method independently (Gesellschaft für Internationale Zusammenarbeit, 2010). Decisions regarding the combination of multiple methods will need to be made on a case-by-case basis, with due consideration to the costs and timings involved.

3.2. Utility of available methods now and into the future

Tables 1 and 2 summarise the available methods for screening and diagnostic timber identification, and assess their relative requirements in terms of future research, cost of application, and status with respect to current usage. There is currently a substantial gap between the potential and realised application of most of the methodologies. Wood anatomical analysis and radiocarbon dating are the only mature disciplines capable of being applied in all cases. Unfortunately, the granularity afforded by wood anatomical analysis is not sufficient for a lot of identification requirements and its application is limited by the number of skilled anatomists available to provide testing services. Radiocarbon dating can be reliably applied to any material, however without the means to identify the species of a sample, radiocarbon information may prove useless in most cases as it is not clear what law may have been breached. The other chemical and genetic methods described in this paper show great promise for future application to a wide range of identification questions, providing much greater resolution than that afforded by wood anatomy. Currently however, the range of taxa that can be identified with these methods is very limited and so their global application is presently minimal.

3.3. Reference collections

All forensic timber identification methodologies require reference material in the form of heartwood for their development, with the exception of genetic analyses which can utilise other plant material such as leaves and cambium to acquire DNA profiles. Heartwood can be obtained directly from a felled tree or from a living tree through coring. Heartwood reference materials are curated in xylaria and to enable correct taxonomic identification, should be collected along with a voucher specimen from the same tree.

Kew Gardens keep a record of xylaria worldwide, the Index Xylariorum, which presently show 83 operational wood collections, and a further 80 which have now been either closed, or absorbed into other collections (Lynch and Gasson, 2010). Although combining collections is not necessarily a bad thing, it usually comes as the expense of professional expertise, where fewer wood anatomists curate larger collections. Given the time required to reach the level of proficiency required for forensic timber identification purposes, time is most definitely of the essence. The greatest barrier to the establishment of a system relying on wood anatomy as an essential first step is the paucity of appropriate wood anatomical expertise worldwide — a deficit which can only be addressed by appropriate recognition, investment and long-term support of wood reference collections and the training of new wood anatomists.

Reduced investment in wood collections and associated staff cut backs are part of a broader trend of reduced support for collection-based science (Funk, 2014), classically termed the 'taxonomic impediment' (de Carvalho et al., 2007, 2005). The knock-on effect of this deficit for forensic timber identification is much more than just a dearth of available wood anatomists. In reality, most methodologies are not ready for forensic use, or where they are, it is only to answer a very narrow suite of specific identification questions. In order to move towards the development of a broader set of forensic timber identification tools, researchers must have access to high quality, taxonomically validated reference collections.

New requirements for forensic timber identification tools arise each time a timber species is listed on the CITES appendices. At present, no consideration is given to the availability of identification tools when new listings are made, and there are no requirements for signatories of the convention to provide reference material or facilitate its acquisition. We contend this presents an unacceptable arrangement, whereby sole responsibility for reference material collection falls to underfunded xylaria. Adding to these difficulties is the paucity of taxonomic clarity in many groups of timber species; without solid taxonomic foundations, it is not possible to develop the required forensic identification tools.

3.4. Transition from research to forensic tool

The final hurdle in the roll-out of any forensic timber identification tool is meeting the strict legal requirements for evidence suitable for presentation in a court of law. These requirements are qualitatively different from those that apply to the acceptance of research into scientific journals, although publication of a method in a peer reviewed periodical is an essential part of the process. The specific challenges are reviewed in detail by Ogden et al. (2009) with respect to DNA forensics, but the general principles apply to all methods. Methods must be subject to extensive validation studies (Peters et al., 2007; SWGDAM, 2012), which assess the ability of tests to achieve the desired outcomes, and characterise the limits within which a test performs as required. Once a test has been forensically validated, it must be applied with due consideration to the requirements for secure chain of custody of evidence (Khan et al., 2010) and in a facility that meets best-practice standards for quality control and quality assurance (Visschedijk et al., 2005). Accreditation of tests and facilities to ISO/IEC 17025 is a means to ensure that these standards are met; however acquiring accreditation is a difficult and expensive process. The development of an externally administered proficiency testing programme is an alternative means of assuring quality which may present a more realistic short term goal for forensic timber identification methodologies at present. For the techniques presented here, only wood anatomy has a significant body of case law as precedent, much of which is in the US court system, dating back to the 1930s.

4. Conclusions

Although a broad range of scientific disciplines boast methodologies suitable for forensic timber identification, they share many of the same underlying requirements, challenges and opportunities for advancement through integrated research and investment efforts. In particular, we highlight the need for improved access to appropriate reference materials to enable effective tests to be developed. Historically, progress towards the development of timber identification tools has proceeded independently in each discipline, often with a sense of competition between proponents of the various methodologies, and a pervading reluctance to accept the validity and future potential of alternative approaches. The tide however, is changing. Several large projects have been undertaken assessing the utility of combining approaches (in parallel or sequentially) to best answer the identification question at hand. In this regard Germany presents a leading example with the Thünen Centre of Competence on the Origin of Timber combining wood anatomy, genetics and forest economics in many collaborative projects, along with stable isotope laboratories and NGOs. The United Nations has also turned its attention to the global requirements for forensic timber identification tools, with the Office on Drugs and Crime (UNODC) convening an expert meeting in December 2014, bringing together the world's experts in the various scientific methods along with law enforcement personnel (UNODC, 2015). A UNODC guidance document on forensic timber identification is expected to be published 2015/2016. We hope this represents an important step in the international community's involvement in furthering the cause of forensic timber identification requirements. There is now a growing acceptance and enthusiasm for the idea that no one method can be a panacea; a future where illegal logging crimes can be routinely prosecuted with robust scientific supporting evidence can only be realised through a synergistic approach to the identification challenges we currently face.

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