CONVENTION ON INTERNATIONAL TRADE IN ENDANGERED SPECIES
OF WILD FAUNA AND FLORA

Twenty-second meeting of the Plants Committee
Tbilisi (Georgia), 19-23 October 2015

Interpretation and implementation of the Convention

Trade controls and marking

TIMBER IDENTIFICATION

This information document has been submitted by the CITES Management Authority of the United States of America in relation to agenda item 14.¹

¹ The geographical designations employed in this document do not imply the expression of any opinion whatsoever on the part of the CITES Secretariat (or the United Nations Environment Programme) concerning the legal status of any country, territory, or area, or concerning the delimitation of its frontiers or boundaries. The responsibility for the contents of the document rests exclusively with its author.
Discussion

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

Eleanor E. Dormontt a, Markus Boner b, Birgit Braun c, Gerhard Breulmann d, Bernd Degen e, Edgard Espinoza f, Shelley Gardner g, Phil Guillery h, John C. Hermanson i, Gerald Koch j, Soon Leong Lee k, Milton Kanashiro m, Anto Rimbawanto n, Darren Thomas o, Alex C. Wiedenhoeft p, Yafang Yin q, Johannes Zahnen q, Andrew J. Lowe a, *,

a Centre for Conservation Science and Technology, School of Biological Sciences, University of Adelaide, Adelaide, SA 5005, Australia
b Agrisolab GmbH, Prof. Rehm Strasse 6, 52428 Jülich, Germany
c Markgrommering Str. 31, 71696 Moehlingen, Germany
d International Tropical Timber Organization (ITTO), Yokohama, Japan
e Thünen Institute of Wood Genetics, Sieker Landstraß e 2, 22927 Großhansdorf, Germany
f National Fish and Wildlife Forensic Laboratory, East Main Street, Ashland, OR 1490, USA
g USDA Forest Service International Programs, 1 Thomas Circle NW, Suite 400, Washington, DC 20005, USA
h Forest Stewardship Council (FSC) International, Charles de Gaulle Straße 5, 53113 Bonn, Germany
i USDA Forest Service, Forest Products Laboratory, Madison, WI 53726, USA
j Thünen Institute of Wood Science, Leuschnerstraße 91, 21031 Hamburg-Bergedorf, Germany
k Forest Research Institute Malaysia, 52019 Kepong, Selangor, Malaysia
l Embrapa Amazônia Oriental, Trav. Enf. Pinheiro s/n, 66, 695-903 Belém, PA, Brazil
m FORWA Centre for Forest Biotechnology and Tree Improvement, Yogjakarta, Indonesia
n Double Helix Tracking Technologies Pte Ltd., 3 Science Park Drive, #02-12/25 The Franklin, Singapore Science Park I, Singapore 118223, Singapore
o USDA Forest Service, Forest Products Laboratory, Madison, WI 53726, USA
p WWF Germany Berlin, Reinhardtstr. 18, 10117 Berlin, Germany
q Forest Anatomy and Utilization Department, Research Institute of Wood Industry, Chinese Academy of Forestry, No. 1 Dongxiaofu, Beijing 100091, China
r USDA Forest Service International Programs, 1 Thomas Circle NW, Suite 400, Washington, DC 20005, USA
s National Fish and Wildlife Forensic Laboratory, East Main Street, Ashland, OR 1490, USA
t Forest Stewardship Council (FSC) International, Charles de Gaulle Straße 5, 53113 Bonn, Germany
u USDA Forest Service, Forest Products Laboratory, Madison, WI 53726, USA
v WWF Germany Berlin, Reinhardtstr. 18, 10117 Berlin, Germany
w Forest Research Institute Malaysia, 52019 Kepong, Selangor, Malaysia
x Embrapa Amazônia Oriental, Trav. Enf. Pinheiro s/n, 66, 695-903 Belém, PA, Brazil
y Double Helix Tracking Technologies Pte Ltd., 3 Science Park Drive, #02-12/25 The Franklin, Singapore Science Park I, Singapore 118223, Singapore
z USDA Forest Service, Forest Products Laboratory, Madison, WI 53726, USA
a WWF Germany Berlin, Reinhardtstr. 18, 10117 Berlin, Germany

A R T I C L E   I N F O

Article history:
Received 24 February 2015
Received in revised form 25 June 2015
Accepted 27 June 2015
Available online xxxx

Keywords:
Wood anatomy
Mass spectrometry
Near infrared spectroscopy
Stable isotopes
Radiocarbon
DNA

A B S T R A C T

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/phyllogeography, 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.

Crown Copyright © 2015 Published by Elsevier B.V. All rights reserved.

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
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 origin 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.

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

Please cite this article as: Dormontt, E.E., et al., Forensic timber identification: It’s time to integrate disciplines to combat illegal logging, Biological Conservation (2015), http://dx.doi.org/10.1016/j.biocon.2015.06.038
Table 2
Diagnostic methodologies for forensic timber identification.

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

E.E. Dormontt et al. / Biological Conservation xxx (2015) xxx
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 timber is often removed from its natural environment. 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.

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 timber is often removed from its natural environment. 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.

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 aids 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 it can provide 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 (Hanea et al., 2005). The approximate felling date of a tree can potentially be determined if timber products possess the outermost 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 phytocamels 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).

2.2.4. Stable isotopes

Assessment 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 14C, otherwise known as radiocarbon, with a half-life of 5730 ± 40 years (Godwin, 1962). 14C decays naturally to 14N, a stable isotope of nitrogen. Formation of 14C occurs predominantly in the upper atmosphere through natural processes and after oxidation to CO2. 14C is mixed throughout the earth’s various carbon pools. Carbon sequestered by plants is fixed from atmospheric CO2 via photosynthesis, and at that point ceases to be exchanged with the environment and decays predictably to 14N. By measuring the ratio of 14C to 12C, 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 14C in the atmosphere were substantially increased due to nuclear bomb testing creating the ‘bomb curve’ in 14C 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 matK and ribulose-bisphosphate carboxylase (rbcL) 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 (Muelner et al., 2011). CITES listed Aquilaria species have also been distinguished from other closely related species using a combination of ITS1 and the trnL–trnF 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 (Nithianyal 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; 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 (Thañh et al., 2010, 2009). Successful assignment to relatively small concession 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
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 utilising 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.

### 3.3. 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 conservation. We propose a revised legal framework for the management of collection which affords the highest possible levels of security and authenticity. This proposed arrangement would be strictly required scientific (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.

### 3.3. 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 conservation. We propose a revised legal framework for the management of collection which affords the highest possible levels of security and authenticity. This proposed arrangement would be strictly required scientific (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.

### 3.3. 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.
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 methods along with law enforcement. 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 methods along with law enforcement.

Acknowledgements

Writing of this paper was supported by the University of Adelaide through salary to the primary author. We would further like to thank the organisers and participants of the United Nations Office on Drugs and Crime Expert Group Meeting, held in December 2014 in Vienna Austria, along with the members of the Global Timber Tracking Network, whose discussions on the issues described in this paper were invaluable.

References


