A Case Study to Establish a Basis for Evaluating Geographic Origin Claims of Timber From the Solomon Islands Using Stable Isotope Ratio Analysis

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Global demand for low-cost forest products is leading manufacturers and traders to source timber and wood products from vulnerable nations and delicate ecosystems. One small island nation, the Solomon Islands, is seeing exploitation of natural resources accelerating to such a point that its natural forests may be exhausted by 2036. The main causes of natural forest loss on the archipelago are unsustainable or illegal logging practices. Various laws in consumer countries require that members of industry ensure that only legally sourced timber is placed onto their respective national markets. Those that break these laws or fail to act in a way that is compliant may be subject to harsh penalties. This study aims to establish scientific data to evaluate claims that timber has originated from the Solomon Islands. This will enable Operators to carry out due diligence analysis and permit members of Law Enforcement to conduct forensic investigations. Eighty timber core samples comprising 13 different genera of tropical trees were obtained from mature trees in two sites in the Solomon Islands (Guadalcanal and Kolombangara islands) during the period August 2019 to November 2019 using a Pickering Punch sampling device. Homogenised core samples were subject to δ^{18}O, δ^{2}H, δ^{13}C, and δ^{34}S stable isotope analysis using elemental analysis-isotope ratio mass spectrometry. Additional stable isotope data from relevant taxa and geographic origins (elevation, geographic co-ordinates) were also included in this research as an initial assessment of differences in stable isotope ratios between countries. Results show that significant differences are evident in the stable isotope ratios of the sampled taxa within the Solomon Islands (Guadalcanal and Kolombangara Islands) and between other countries. These data can be used as a basis of evaluation to evaluate origin claims of timber or wood products from the Solomon Islands, particularly Kolombangara Island. Furthermore, in the right context, these data can also be used to establish whether timber or wood products declared to be from origins other than the Solomon Islands have stable isotope ratios that are consistent with data from the Solomon Islands. If not, this would suggest foreign timber/forest products are from elsewhere and are being passed-off as originating from the Solomon Islands.

Keywords: stable isotopes, Solomon Islands, tropical timber, EUTR, Lacey Act amendment, EA-IRMS

INTRODUCTION

The Solomon Islands is an archipelago comprising seven major islands: Guadalcanal, Choiseul, Santa Isabel, New Georgia, Malaita, and Makira (or San Cristobal), and a host of smaller ones. They are extensively forested with 88% of the country under forest cover. More than 80% of the country is under high rainforest with the remaining 8% mainly swamp forest, including mangroves, and upland forests. The rainforest has generally fewer timber species than surrounding countries, with around 60 reaching large sizes. The major species harvested are *Pometia pinnata*, *Calophyllum* sp., and a mixture of "whitewoods" (FAO and Pauku, 2009).

The Solomon Islands is China's second largest source of tropical timber by country (after Papua New Guinea) (Smyth, 2018), yet the landmass of the entire country is only twice the size of Beijing. By comparison, the largest source of tropical logs, Papua New Guinea constitutes roughly half of the landmass of New Guinea, the world's second largest Island at 785,753 km^2. The heavy reliance on such a small territory for timber is rapidly depleting the Solomon Islands' forest cover, biodiversity, and natural resources at rates several NGOs describe as "unsustainable." If logging continues at its current rate, the island nation is expected to be deforested by 2036 (Rarawa, 2012). Given the magnitude of the situation, there are serious questions considering how this can be happening in a way that is compliant with law. One NGO report presents evidence that the extraction of timber from the Solomon Islands is not happening legally (Global Witness, 2018).

In 2015 over 2.5 million cubic metres of logs were exported from the Solomon Islands (Global Witness, 2018), this is over 10 times the annual sustainable yield. It is difficult to perceive how such a small nation could place such a large volume of timber on the global market. There is speculation that declared imports from the Solomon Islands may have originated elsewhere, such as Papua New Guinea, and that this occurs to launder illegal timber into the global supply. However, declared import and export data for the Solomon Islands do not support this hypothesis (Global Witness, 2018). Unless timber traders who engage in illegal practices are shipping logs to the Solomon Islands for re-export, it seems the major concern is that timber originating from the Solomon Islands is often unsustainably harvested and possibly illegally harvested rather than mislabelled with respect to its geographic origin.

Much of the timber exported from the Solomon Islands is destined to be turned into plywood or other composite products for export and is not necessarily consumed domestically in China. European Union Timber Regulation (EUTR) (Regulation (EU) No 995/2010, 2016) and the Lacey Act (2008) both demand that timber and timber products are obtained legally before they are placed on the respective EU and United States markets. EUTR places penalties against companies that are the first to place timber products on the EU market if they do not enact a due diligence/due care system to ensure the timber is from a legal source. The Lacey Act may be used in criminal and civil cases to enact penalties against violators that place illegally sourced timber on the United States market.

The main islands/regions for logging in the Solomon Islands are: Western Province (includes the islands of Vella Lavella, Kolombangara, New Georgia, Rendova, Vangunu, and Ngatokae), Choiseul Province, Isabel Province, Guadalcanal Province, Malaita Province, and Makira Province (FAO and Pauku, 2009). Kolombangara Island is the base of operations of Kolombangara Forest Products Ltd. (KFPL) and, to date, this is the only Forest Stewardship Council (FSC) certified source of timber within the Solomon Islands. With FSC's mandatory chain of custody, sustainability requirements, regular audits, GPS mapping of individual trees amongst many other facets, FSC certified timber from KFPL has negligible risk of illegality. This is contrary to timber from other islands within the Solomon Islands which have elevated risks of illegality. Therefore, being able to verify that timber is from Kolombangara Island is a way to demonstrate that the timber is likely legal.

The ambitions of this research were to define the ranges of stable isotope ratios from multiple species of trees from Kolombangara Island by analysing timber samples extracted from living trees. Data from samples collected from origins other than Kolombangara Island allow for the demonstration of differences which is useful to imply further potential. Analysis of the data helps us to:

- Assess what differences are available in the stable isotope ratios of trees from different provinces within the Solomon Islands and outside of the Solomon Islands.
- Utilise these methods to check whether the declared origin of the Solomon Islands timber is consistent with data from the Solomon Islands.

If significant differences in the stable isotope ratios of trees from different provinces within the Solomon Islands are evident, this will be of great benefit to legal investigation teams in demonstrating that seized timber is illegal or at risk of being illegal. If the isotope ratios of trees from within different provinces of the Solomon Islands are relatively homogenous, this would mean that it may not be necessary to collect reference samples from all provinces to establish that the timber is from the Solomon Islands. However, it could mean that to question its legality, further evidence would be required to demonstrate that timber is not from Kolombangara Island.

Stable isotope analysis is a widely accepted analytical discipline and has a long history, with many laboratories adopting the technology around the world. Since the beginning of the 21st century, the technique has become well established as a means of verifying the origin of food and drink (Boner and Förstel, 2004; Kelly et al., 2005; Heaton et al., 2008; Pilgrim et al., 2010; Li et al., 2015) and is established as an analytical technique that can be used in legal cases (Camin et al., 2017). The same principles used to authenticate food were later applied to timber provenance research (Boner et al., 2007; Keppler et al., 2007; Horacek et al., 2009; Kagawa and Leavitt, 2010; Gori et al., 2012, 2018; Rees, 2015; Watkinson et al., 2020). Verifying the origin of timber typically depends on comparing an unknown sample against an authentic reference database for a region or territory. The technique is used routinely to assess legality, compliance with

labelling legislation (DEFRA, 2018; Forest Trends, 2019), and its use to conduct due diligence is advocated by EUTR (Regulation (EU) No 995/2010, 2016). The United Kingdom Office for Product Safety and Standards (OPSS) within the Department for Business, Energy and Industrial Strategy (BEIS) use this technique to ascertain the veracity of timber origin claims.

MATERIALS AND METHODS

Sampling

Kolombangara Forest Products Ltd., provided FSC with a list of species ranked in importance in terms of their own supply and importance to the Solomon Islands. This list was comparable to the list of economically important species published in the Solomon Islands Forestry Outlook (FAO and Pauku, 2009). The top 10 species intended for sampling were a mix of native and introduced trees including:

- *Eucalyptus deglupta*
- *Gmelina arborea*
- *Campnosperma brevipetiolatum*
- *Swietenia macrophylla*
- *Terminalia calamansanai* and *Terminalia brassii*
- *Agathis* sp.
- *Tectona grandis*
- *Acacia* sp.
- *Calophyllum inophyllum*
- *Palaquium* sp.

In addition to this, Solomon Islands Law prohibits the export of unprocessed logs of *Vitex cofassus, Intsia bijuga, Gmelina moluccana*, and *Pterocarpus indicus* (Australian Government, 2014; Global Witness, 2018) meaning that samples of these trees would also prove valuable.

Sixty-eight samples of timber were collected on Kolombangara Island in August, September, and November of 2019. Twelve samples of timber were also taken from Guadalcanal Island in September and November 2019 for analysis. Samples were collected by trained collectors who were able to identify the species or genus of the tree in the field. Herbarium voucher material was collected for some specimens, but not all.

A Pickering Punch (Agroisolab UK, Welburn, United Kingdom), a type of hammer-driven bore, was used to collect cores of timber 12–18 cm in length and 1.3 cm wide from living trees. Samples were then transferred from the Pickering Punch into cardboard tubes along with silica gel which in turn, were sealed inside 500 ml evacuated bags to aid drying and protect the sample from the humid air in the local environment. August and September samples were collected using 30 g silica gel per plug and no perforations were made in the acid-free cardboard tubes, however, field tests found this did not adequately facilitate drying, and some cores presented with hyphae upon receipt at the Plant Quarantine Unit at the Royal Botanic Gardens, Kew, United Kingdom. Extensive rot is a concern with respect to stable isotope analysis, Filley et al. (2002) demonstrates that brown rot fungi can cause significant differences in the $\delta^{13}C$ in lignin and polysaccharides in spruce

sapwood over a sufficient timespan, therefore it was necessary to treat samples to prevent unwanted degradation and re-consider collection packs.
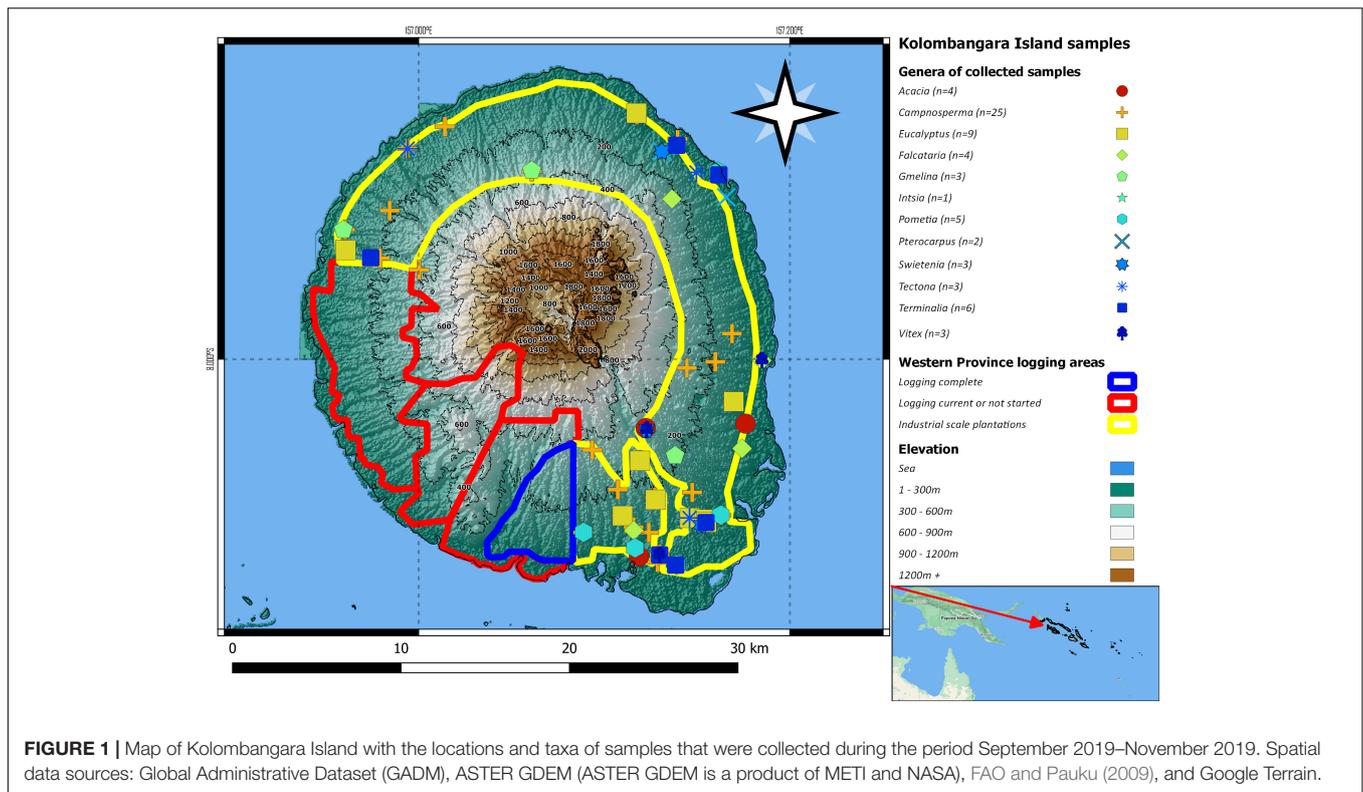
Collecting samples of biological material, such as wood, from the tropics without spoilage is challenging due to the humidity and biodiversity of tropical rainforest. Controlling for mould was therefore equally challenging. To prevent mould growth, collection packs were redesigned for the November collection to allow for better drying without the need to recycle the silica gel, this included 30–40 perforations 6 mm in diameter in each cardboard tube and increasing the mass of silica gel to 100 g per plug, as well as drying and replacing/recharging silica gel prior to sample collection. Samples were shipped to the Royal Botanic Gardens at Kew, destined for the World Forest ID (WFID) collection (Gasson et al., 2020), and were held in quarantine pending approval. To eliminate the risk of pathogenic fungi entering the United Kingdom, samples were heated to 121°C at 15 psi for 30 min before they were released into the WFID collection for storage and analysis.

GPS data, photographs of the trees and leaves, descriptions, and comments about the sampled trees were recorded in a mobile phone application named TreeSnap (Crocker et al., 2019; TreeSnap version 1.15.3 Department of Entomology and Plant Pathology, University of Tennessee, Institute of Agriculture, Knoxville, TN, United States). The data from this collection have since been moved to the WFID application (World-ForestID version 1.2.0, Department of Entomology and Plant Pathology, University of Tennessee, Institute of Agriculture, Knoxville, TN, United States). **Figure 1** shows the locations of the samples that were collected from Kolombangara Island.

Additionally, this report contains data from: four samples of *T. grandis* from Papua New Guinea which were collected using an electric drill (Makita BDF 451, Nagoya, Japan) and a 20 cm long 10 mm diameter auger in April 2012 near the Adelbert mountain range, 10 samples of *Calophyllum* sp. from Kolombangara Island that were collected by KFPL in 2015 as part of an FSC project, 20 samples of *Calophyllum* sp. from Yang Zai Forestry in southern Taiwan that were collected by FSC in November 2017, two samples of *P. pinnata* from New Britain (Papua New Guinea, Bismarck Archipelago) in May 2020, and six samples of *Pterocarpus soyauxii* that were obtained from the Precious Woods Group (PWG) and Compagnie des Bois du Gabon (CBG) concessions in Gabon in June 2019 (**Figure 2**). Samples from Gabon were collected as part of an effort to define the stable isotope ratios of various species in two FSC concessions and are also evaluated in Watkinson et al. (2021). These data are to be used as a preliminary assessment of differences between geographic origins. At present, the collections of reference samples are not extensive, and any inferences drawn from their evaluation can only be appraised in the context of their current limitations.

Measurement

Any samples that were affected by hyphae had the mould removed prior to preparation in accordance with advice in Horacek et al. (2018) and Beeckman et al. (2020). Samples were initially dried at 103°C before grinding/drilling. Samples

FIGURE 1 | Map of Kolombangara Island with the locations and taxa of samples that were collected during the period September 2019–November 2019. Spatial data sources: Global Administrative Dataset (GADM), ASTER GDEM (ASTER GDEM is a product of METI and NASA), FAO and Pauku (2009), and Google Terrain.

were drilled using a 7 mm drill bit to the depth of 10–13 cm from the bark side to the pith side to grind them to a coarse powder. All materials were subsequently milled into a fine powder using a ball-mill (Retsch MM220–Haan, Germany). The powder was extracted in a soxhlet apparatus over 6 h with non-polar (dichloromethane) and polar (methanol) solvents which were then dried in a laboratory-type drying cabinet for at least 1 h. Finally, the samples were stored in air-tight sample vials and weighed for analysis.

To avoid equilibration or humidity effects in the oxygen and hydrogen analysis, the weighed-in samples were equilibrated overnight in desiccators with a defined humidity of 10.6%. Afterwards the samples were vacuum dried for at least 2 h.

Sample measurements were corrected against in-house standards at the beginning, middle, and end of each measurement run. In-house standards are traceable back to certified reference materials enabling measurements to be reported relative to an internationally defined standard; for hydrogen and oxygen isotope ratio analysis, Vienna Standard Mean Ocean Water (VSMOW) is used. For carbon isotope ratio analysis, Vienna Pee Dee Belemnite (VPDB) is used. For sulphur isotope ratio analysis Vienna Canyon Diablo Troilite (VCDT) is used. The in-house standards used were 1,4-Dihydroxyanthraquinone (Merch-Schuckhardt) for $\delta^{18}O$ and $\delta^{2}H$, L-leucine (Carl Roth GmbH + Co. KG, Karlsruhe, Germany) for $\delta^{13}C$ and $\delta^{15}N$, and L-cysteine (Carl Roth GmbH + Co. KG, Karlsruhe, Germany) for $\delta^{34}S$. In-house standards are also controlled in Agroisolab's free intercomparison testing platform "Agroisolab-KPT" which routinely operates with over 20 isotope

laboratories. Measurements are reported in per mil (‰) and were made in accordance with processes outlined in Boner et al. (2007).

$\delta^{18}O$ and $\delta^{2}H$ measurement was performed using two Isotope Ratio Mass Spectrometers (IRMS) in a master/slave configuration (Isoprime, Elementar, Cheadle, United Kingdom) with each IRMS measuring one isotope ratio; $\delta^{18}O$ or $\delta^{2}H$. This configuration provides excellent stability because the magnetic field and accelerating voltage remain constant on each IRMS. The working temperature for pyrolysis is > 1530°C and HT-PyrOH is performed with a covalently bonded silicon carbide tube (patented by Agroisolab GmbH, Julich, Germany) filled with glassy carbon chips and coal powder. The mode Combined Uncertainty (u_c) for $\delta^{18}O$ was 0.2‰ and for $\delta^{2}H$ was 1.3‰.

$\delta^{13}C$ measurement was performed using an Elemental Analyser (EA3000, Eurovector, Milano, Italy) in combination with IRMS (Nu Horizon, NU-Instruments—Wrexham, Wales). The working temperatures are 1021°C for oxidation and 600°C for reduction. Reduction is carried out in the presence of copper. The mode Combined Uncertainty (u_c) for $\delta^{13}C$ was 0.1‰.

$\delta^{34}S$ measurement was performed using an Elemental Analyser (EA3000, Eurovector, Milano, Italy) with IRMS (Isoprime, Cheadle, United Kingdom). A one tube combustion (oxidation and reduction in one tube) is used to solve issues caused by SO_3. Combustion water is directly trapped with magnesium perchlorate at the end of the tube. The working temperature is 1000°C. The mode Combined Uncertainty (u_c) for $\delta^{34}S$ was 0.2‰.
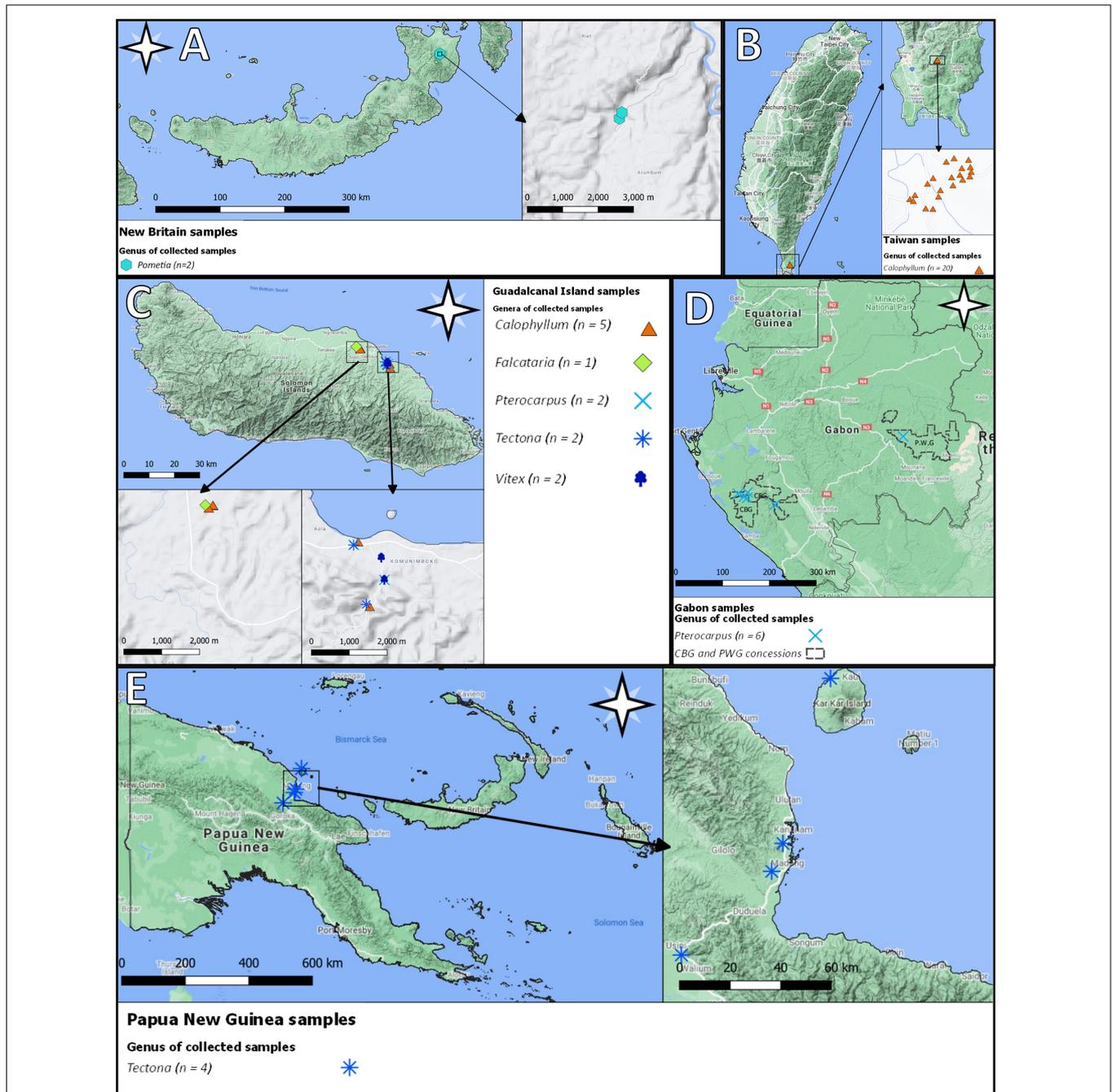
FIGURE 2 | Locations of reference samples in **(A)** New Britain (Papua New Guinea), **(B)** Taiwan, **(C)** Guadalcanal Island (Solomon Islands), **(D)** Gabon, and **(E)** Papua New Guinea. Spatial data sources: Global Administrative Dataset (GADM), and Google Terrain.

Data Analysis

As many of the taxa analysed in this project had not been previously analysed by Agroisolab or other laboratories, and the quantities of samples were relatively low, multi-variate analysis methods were not used to help draw conclusions from the data. Instead, univariate analyses were performed to show differences between distributions of means such as Student's *T*-test and ANOVA, or to assess co-variance such

as regression as well as boxplot visualisations (Microsoft Excel 2016, Microsoft Corporation, Redmond, WA, United States). Three well-sampled taxa (*E. deglupta*, *Terminalia* spp., and *C. brevipetiolatum*) were assessed in SAGA GIS 2.3.2 (Departments for Physical Geography, Hamburg and Göttingen, Germany) for spatially related patterns in their data using variogram analysis (variance/distance) and representing interpolated data using Universal Kriging (Global). This method was used to

describe variance/distance related patterns in the data *via* graphical representation.

RESULTS

In most analysed taxa, oxygen stable isotope ratios ranged between approximately 19.5 and 21.5‰ (**Table 1**). There are differences in the mean values of the oxygen isotope ratios of the taxa, ANOVA has a low *P*-value (<0.05) indicating that the differences are significant. However, some results show similar means such as *Vitex* and *Eucalyptus* which are not significantly different as the means are nearly identical. *Acacia* stands out as being significantly enriched in ^{18}O relative to most other sampled timbers in the dataset. The greatest differences in oxygen isotope ratios exist between *Acacia*, *Vitex,* and *Eucalyptus* (2.4‰ difference between means). A wide range of hydrogen stable isotope ratios is evident among the different taxa indicating that there appears to be species effect in the data, i.e., different taxa in the same region may have significantly different stable isotope ratios.

Acacia samples from Kolombangara Island had remarkably negative carbon stable isotope ratios in comparison to other analysed taxa from the island. Several ranges of δ^{13}C isotope ratios are evident among the different samples of timber, further supporting the hypothesis that different trees on the same site can have significantly different stable isotope ratios. Reference samples of *Acacia* show two extremes relative to the dataset, significantly negative δ^{13}C stable isotope ratios and significantly enriched δ^{18}O isotope ratios.

A remarkably wide range of sulphur isotope ratios was evident among the sampled taxa ranging from approximately $+6$‰ in *Calophyllum* to $+15$‰ (11‰ range) in *Campnosperma*. Even taking the range into context, all samples can be said to be enriched in ^{34}S. The wide ranges of values between different taxa can also be found in the δ^2H and δ^{13}C isotope ratios of the samples. ANOVA of *Acacia*, *Pometia*, *Eucalyptus*, *Vitex*, *Calophyllum*, *Tectona*, *Terminalia*, *Campnosperma*, and *Falcataria* δ^{18}O, δ^2H, δ^{13}C, and δ^{34}S yielded P values less than

TABLE 1 | Stable isotope ratio data from taxa sampled in the Solomon Islands, Gabon, Taiwan, Papua New Guinea, and New Britain.

Origin	Taxa	N samples	δ^{18}O vs. VSMOW (‰)			δ^2H vs. VSMOW (‰)			δ^{13}C vs. PDB (‰)			δ^{34}S vs. CDT (‰)		
			Mean	σ	Range	Mean	σ	Range	Mean	σ	Range	Mean	σ	Range
Kolombangara Island														
	Acacia mangium	4	+22.3	0.5	1.2	−81.5	9.7	22.9	−31.1	0.4	0.9	+10.0	0.8	1.7
	Campnosperma sp.	25	+20.6	0.4	1.7	−82.8	3.5	13.0	−28.3	0.7	2.7	+11.3	2.3	8.4
	Eucalyptus deglupta	9	+19.9	0.4	1.2	−104.7	8.7	25.3	−29.2	0.5	1.5	+7.4	1.1	3.1
	Falcataria sp.	4	+20.2	0.3	0.6	−98.2	2.6	5.3	−27.9	0.3	0.7	+12.6	0.5	1.1
	Gmelina sp.	3	+21.0	0.2	0.4	−82.8	8.0	15.1	−28.5	0.6	1.2	+7.9	1.2	2.3
	Intsia bijuga	1	+21.1			−75.9			−27.2			+7.4		
	Pometia pinnata	5	+20.5	0.5	1.1	−84.2	3.6	8.1	−29.6	0.5	1.2	+8.9	0.9	2.2
	Pterocarpus indicus	2	+21.3		0.2	−67.4		5.7	−27.0		0.3	+11.8		0.1
	Swietenia macrophylla	3	+21.5	0.5	0.9	−70.8	4.5	8.9	−29.1	0.9	1.8	+9.2	0.9	1.6
	Tectona grandis	3	+20.3	0.4	0.7	−68.8	8.5	16.8	−28.5	0.7	1.4	+10.3	1.1	2.2
	Terminalia sp.	6	+20.4	0.4	1.2	−69.1	13.8	37.7 (19.7)*	−28.3	0.8	2.1	+10.8	2.4	6.6
	Vitex sp.	3	+19.9	0.2	0.3	−79.8	4.6	8.3	−29.0	0.3	0.6	+11.2	0.6	1.0
	Calophyllum sp.	10	+20.6	0.3	0.8	−67.0	5.1	14.1	−28.5	0.7	2.1	+7.0	0.8	2.7
Guadalcanal Island														
	Calophyllum sp.	5	+21.2	0.2	0.7	−75.7	6.1	15.9	−28.4	0.7	1.9	+5.6	3.8	10.3 (2.0)*
	Falcataria sp.	1	+22.0			−98.1			−27.3			+12.0		
	Pterocarpus indicus	2	+21.7		0.2	−72.0		1.3	−26.8		0.7	+7.8		1.3
	Tectona grandis	2	+20.9		1.2	−63.9		9.9	−28.2		1.6	+7.5		1.6
	Vitex sp.	2	+20.0		0.1	−75.9		0.3	−29.5		0.1	+9.4		0.5
Gabon														
	Pterocarpus soyauxii	6	+23.2	0.4	0.9	−49.8	7.1	18.0	−28.0	1.4	4.0	+11.9	1.0	2.7
Taiwan														
	Calophyllum sp.	20	+21.7	0.3	1.0	−56.2	5.0	15.5	−28.3	1.4	4.0	+8.4	0.9	1.8
Papua New Guinea														
	Tectona grandis	4	+18.2	1.0	2.2	−88.6	16.3	36.5	−28.7	0.6	1.2	+4.1	3.7	7.3
New Britain														
	Pometia pinnata	2	+19.6		0.1	−89.6		7.0	−28.0		1.8	+3.2		0.9

Values within brackets are the ranges if outlier values are removed.

0.05 in all cases and indicates that there is a significant difference between the mean values of each stable isotope ratio of each genus. On its own, this is not conclusive as the sample size for each genus was relatively small but is indicative that different taxa may be expected to have different stable isotope ratio profiles even on an island as small as Kolombangara. It should also be noted that the mean range of sulphur isotope ratios in each genus from Kolombangara Island is not so wide ($3.0 \pm 2.35\text{‰}$).

$\delta^{18}O$ and δ^2H are expected to be well correlated systems where excessive evaporation does not occur Craig (1961). One may reason that this trend should be observable in $\delta^{18}O$ and δ^2H in wood given that oxygen and hydrogen in timber originate from water. In some sampled taxa this trend is evident, however, in *Eucalyptus* sp. (Pearson's R = 0.03), *T. grandis* (Pearson's R = −0.40), *Falcataria* sp. (Pearson's R = 0.30), and *Campnosperma* sp. (Pearson's R = −0.06), this relationship is either weak or not currently evident. This may be due to the low level of sampling, however, 25 samples of *Campnosperma* sp. were obtained from Kolombangara Island. It is more likely that the relationship cannot be established due to the lack of an adequate range of values being present in the reference samples. To evaluate these relationships further in these taxa, it will be necessary to obtain and analyse more samples from origins that are far from the Solomon Islands (i.e., where different ranges of values are more likely to occur). This may mean sampling timbers from countries where the species is not of concern with respect to legality (e.g., plantation *Eucalyptus*) to develop better models for evaluation.
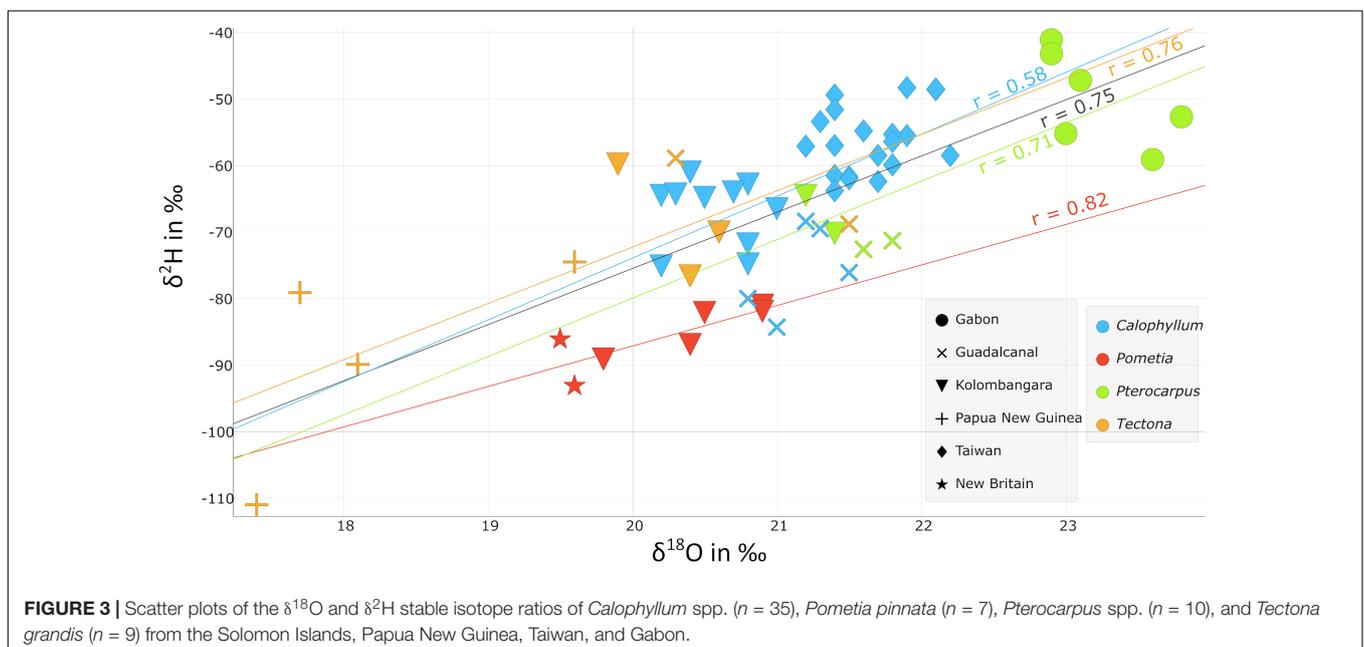
Though the values of the stable isotope ratios of the four taxa shown in **Figure 3** are different to one another, there appears to be an offset between species in the oxygen and hydrogen stable isotope ratios. This may be of use as it could enable development of statistical models built around a single taxon primarily with lower sampling occurring on other taxa and
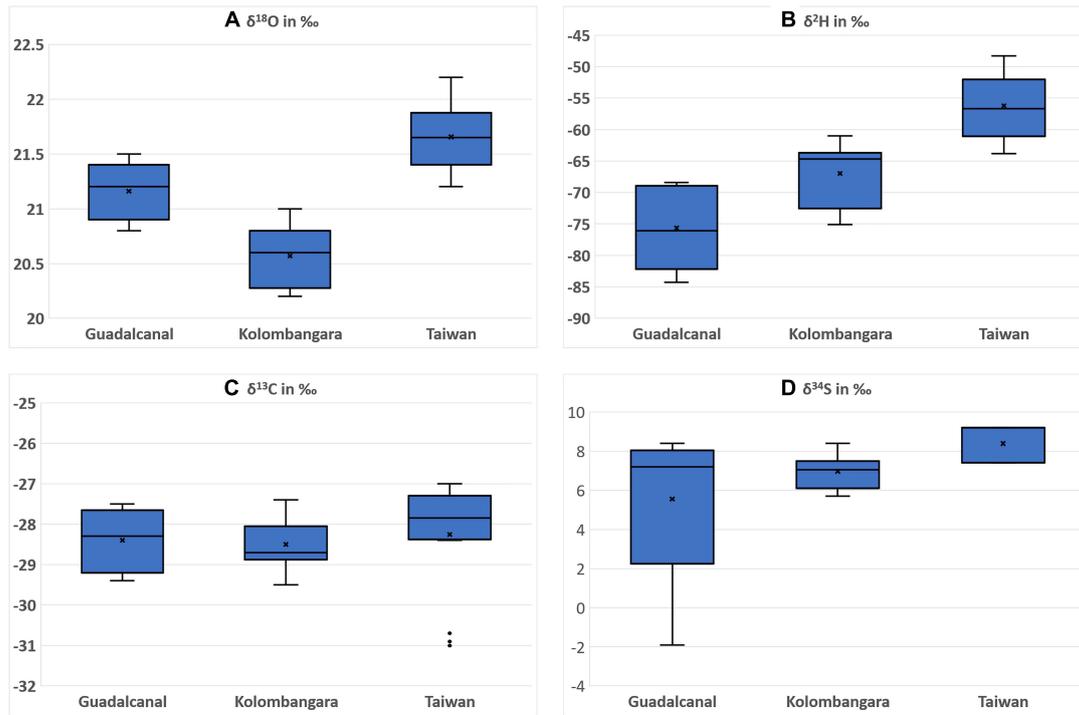
simply relating the two to one another if this trend is further evaluated. These relationships have been referred to as "Dunbar lines" (Dunbar and Wilson, 1983). If the offset between the taxa can be controlled over a sufficiently wide geographic range and range of values with at least 30 locations per taxa, it should be possible to calculate $\delta^{18}O$ and δ^2H between different types of wood. This is advantageous as it would alleviate the heavy burden of comprehensively sampling all concerned species in every possible location.

There are significant differences in the $\delta^{18}O$, δ^2H, and $\delta^{34}S$ stable isotope ratios of *Calophyllum* from regions that were sampled in Kolombangara Island, Guadalcanal Island, and Taiwan as judged by ANOVA ($P < 0.05$). This is promising as not only can a differentiation be established between *Calophyllum* spp. from two countries (Taiwan and Solomon Islands), but the data suggest that there is a chance there may be significant differentiation in timbers from different islands within the Solomon Islands (**Figure 4**). It would only be possible to discover this trend with further sampling of other islands that are important for the logging industry within the Solomon Islands, however, a method that is able to differentiate timber on an island basis would likely be very useful to support questions of legality on timber products that originated from the Solomon Islands.
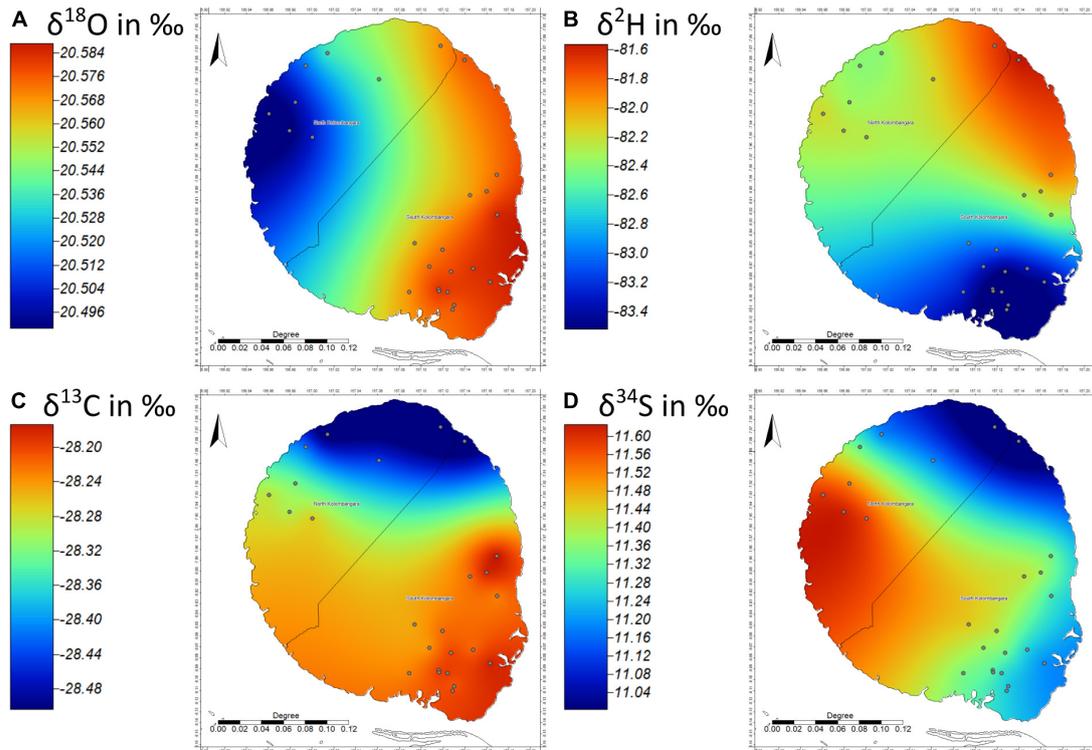
Campnosperma brevipetiolatum Volkens

Campnosperma brevipetiolatum Volkens was the most frequently sampled species in the project with 25 samples collected from different parts of Kolombangara Island. $\delta^{18}O$, δ^2H, and $\delta^{34}S$ isotope data for *Campnosperma* sp. have the widest ranges of all sampled taxa. This may be because the data paint a more realistic depiction of the variance that occurs on the island and perhaps should be used as a template in that regard. **Figure 5** shows there are very weak trends in the stable isotope ratios of the trees across the island judging by the patterns and ranges evident in

FIGURE 3 | Scatter plots of the $\delta^{18}O$ and δ^2H stable isotope ratios of *Calophyllum* spp. (*n* = 35), *Pometia pinnata* (*n* = 7), *Pterocarpus* spp. (*n* = 10), and *Tectona grandis* (*n* = 9) from the Solomon Islands, Papua New Guinea, Taiwan, and Gabon.

FIGURE 4 | Boxplots of the (A) oxygen stable isotope ratios, (B) hydrogen stable isotope ratios, (C) carbon stable isotope ratios, and (D) sulphur stable isotope ratios of *Calophyllum* spp. from Guadalcanal Island (SI) (*n* = 5), Kolombangara Island (SI) (*n* = 10), and Taiwan (*n* = 20).

FIGURE 5 | Universal Kriging Isoscapes of (A) $\delta^{18}O$, (B) $\delta^{2}H$, (C) $\delta^{13}C$, (D) and $\delta^{34}S$ of *Campnosperma brevipetiolatum* from Kolombangara Island (*n* = 25), Solomon Islands. Note that the range displayed in the *color* scales is within the u_c for $\delta^{18}O$, $\delta^{13}C$, and $\delta^{34}S$ and is illustrative of a lack of significant difference across the island.

the isoscapes. The overall spatial trend in the data as represented by the Universal Kriging models demonstrates that the ranges of $\delta^{18}O$, $\delta^{13}C$, and $\delta^{34}S$ are within the Combined Uncertainty (u_c). Empirical variogram analysis shows that differences in the values do not appear to be strongly related to distance as regressions of the $\delta^{18}O$ and δ^2H isotope ratios with the elevation of the samples yield Pearson's R scores of −0.24 and −0.02, respectively. This means that distance between sampling sites and/or elevation of the sampled trees does not describe much of the observable variation in the *Campnosperma* data suggesting that the observed variance is due to a combination of random natural variation and measurement uncertainty in *Campnosperma* sp. from Kolombangara Island. If the variation is due to natural variation, the ranges of values in the $\delta^{18}O$, δ^2H, and $\delta^{13}C$ isotope ratios of the samples, 1.7, 13, and 2.7‰, respectively, are comparable to ranges of variation in stable isotope ratios between different trees on the same site (intra-site variation) as reviewed by Leavitt (2010). This is of benefit as it illustrates that an *n* of 25 samples in an area as large as Kolombangara Island appears sufficient to characterise stable isotope variation in accordance with the methods used.
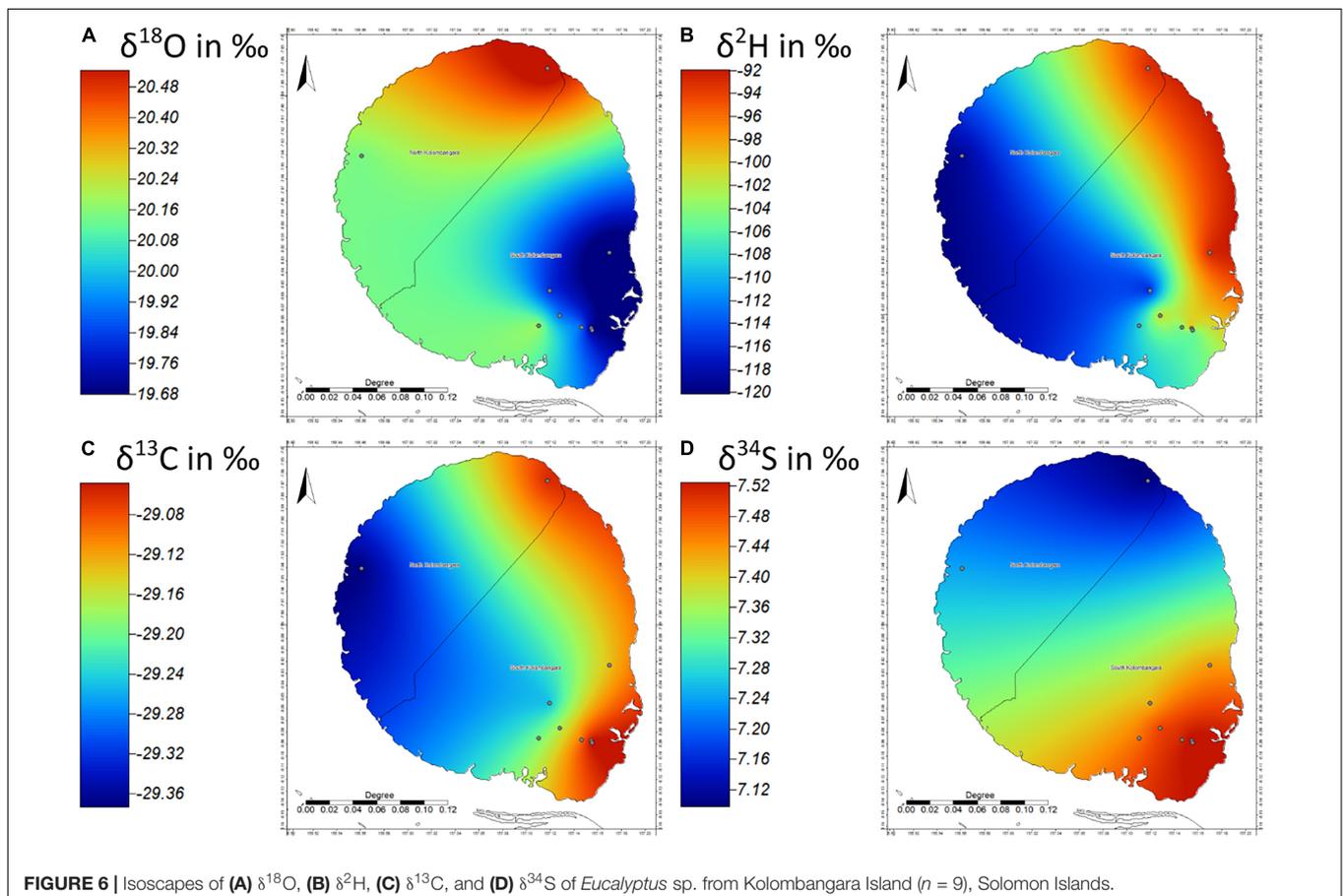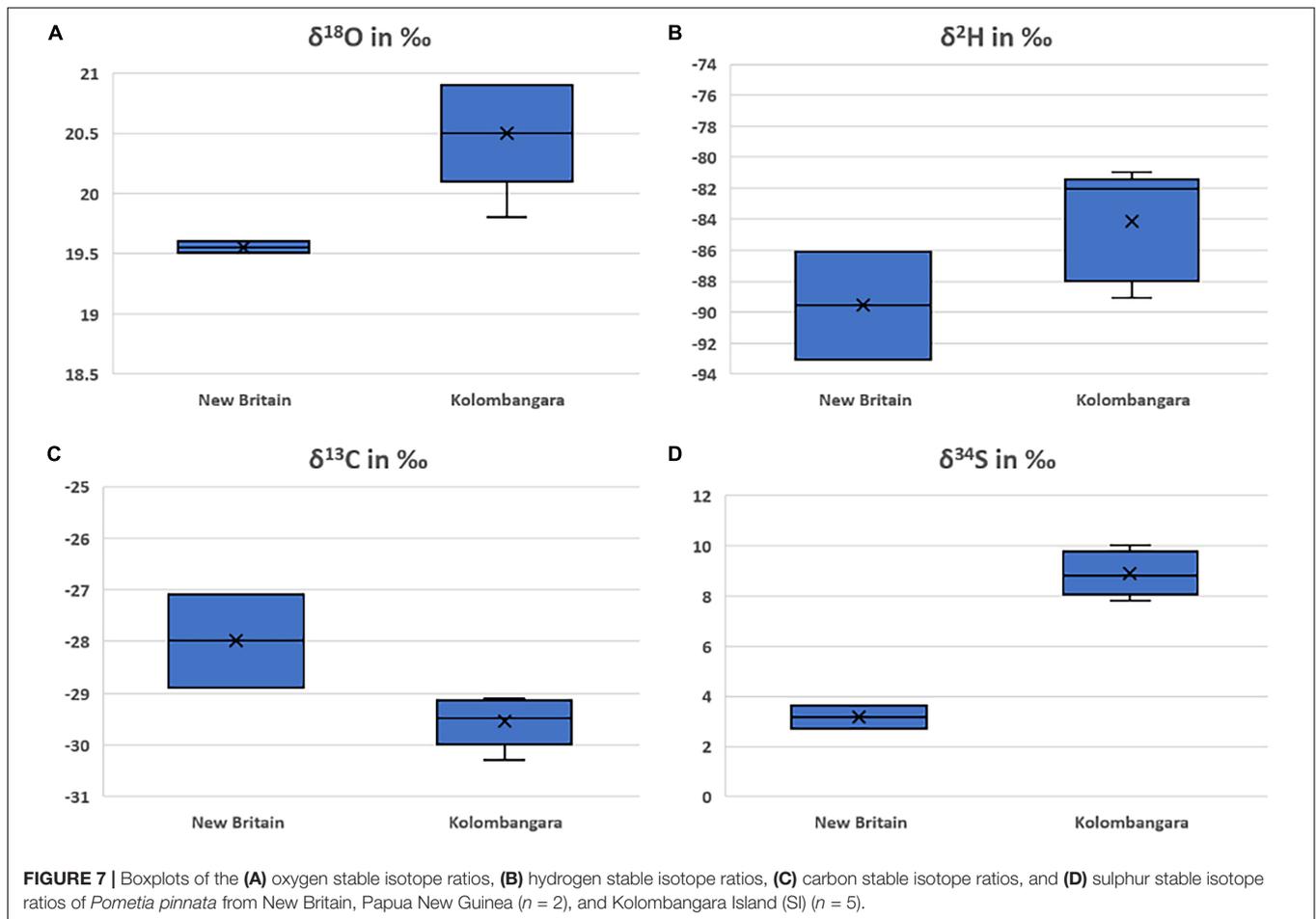
Eucalyptus sp.

Eucalyptus was the third most sampled taxon in this project (*n* = 9). Overall, *Eucalyptus* samples had the most negative δ^2H

isotope ratios (mean = −104.7 ± 8.7‰) and the second most negative $\delta^{34}S$ isotope ratios (**Figure 6**). Empirical Variogram analysis of the *Eucalyptus* data shows that the distance between samples can explain up to 44% of the variation in the data of the δ^2H isotope ratios and 12% in the $\delta^{18}O$ isotope ratios. Variation in hydrogen isotope ratios is often linked to elevation (Bowen and Revenaugh, 2003), however, the Pearson's R for $\delta^{18}O$ and δ^2H with elevation was −0.29 and −0.47, respectively, suggesting that elevation explains only a small portion of the observable variance in the data. The fact that the Pearson's R had a negative result in both cases is also surprising as this suggests that elevation and δ^2H or $\delta^{18}O$ are inversely related on Kolombangara Island. This contrasts with expectations as normally δ^2H or $\delta^{18}O$ become more negative with increasing elevation rather than becoming more enriched.

Pometia pinnata

The samples of *P. pinnata* from New Britain are more depleted in ^{18}O and ^2H than samples from Kolombangara Island (**Figure 7**). It does not appear that the reason for this difference is due to the elevation of where the trees grew as the samples from New Britain were collected at approximately 200 m elevation whereas the samples from Kolombangara were collected between 100 and 200 m elevation. The $\delta^{18}O$ and δ^2H are well-correlated and have a Pearson's R of 0.82 (**Figure 3**), this is expected

FIGURE 6 | Isoscapes of **(A)** $\delta^{18}O$, **(B)** δ^2H, **(C)** $\delta^{13}C$, and **(D)** $\delta^{34}S$ of *Eucalyptus* sp. from Kolombangara Island (*n* = 9), Solomon Islands.

FIGURE 7 | Boxplots of the **(A)** oxygen stable isotope ratios, **(B)** hydrogen stable isotope ratios, **(C)** carbon stable isotope ratios, and **(D)** sulphur stable isotope ratios of *Pometia pinnata* from New Britain, Papua New Guinea ($n = 2$), and Kolombangara Island (SI) ($n = 5$).

as $\delta^{18}O$ and δ^2H are correlated in meteoric precipitation. The *P. pinnata* from New Britain are more enriched in ^{13}C than samples from Kolombangara Island whereas samples from Kolombangara Island are more enriched in ^{34}S than the two samples from New Britain.

Pterocarpus spp.

Though the overall quantities of *Pterocarpus* spp. that have been analysed and presented within this report are small, there are significant differences in the $\delta^{18}O$, δ^2H, and $\delta^{34}S$ ($P < 0.05$ in all cases) between specimens from locations that were sampled in Kolombangara Island, Guadalcanal Island, and Gabon as judged by ANOVA. This is promising as it demonstrates the potential for differentiation within the Solomon Islands provinces and between different nations that produce *Pterocarpus* spp. given that it is pantropical and is subject to overharvesting.

Tectona grandis

Significant differences between the $\delta^{18}O$ ($P < 0.05$) and δ^2H ($P < 0.05$) isotope ratios of *T. grandis* from Guadalcanal Island, Kolombangara Island, and Papua New Guinea are evident (**Table 1**). This result is promising for future sampling and to be able to address the question of whether exported/imported timber from the Solomon Islands is truly from its declared origin,

or whether the timber is from another origin that is a producer of Teak (e.g., Papua New Guinea, Myanmar, and Indonesia). The question of origin is especially important for *T. grandis* as it is one of the most widely used tropical hardwoods in plantations around the world.

Terminalia sp.

Terminalia sp. was the third most sampled timber from Kolombangara Island ($n = 6$) and thus was subjected to variogram analysis to investigate spatial patterns in the data. Empirical Variogram analysis shows that an insignificant ($<1\%$) amount of variance of the data for all analysed stable isotope ratios can be explained by the distance between sampling sites. This is also evident in **Figure 8** as there appears to be very little in terms of the range of values of the stable isotope ratios across the island with the exception of the $\delta^{34}S$ (**Figure 8D**). In this case the Empirical Variogram shows the distance between samples explains 0.13% of the variance in $\delta^{34}S$; this appears to contradict the north to south trend evident in **Figure 8D**. The reason for the insignificant correlation is that the sample on the north-eastern edge of the island is an outlier relative to the other samples and the Empirical Variogram treats it as such. This suggests that there is either no strong spatial structure to the data for *Terminalia* sp. on Kolombangara Island, the variance is random, or that

there were too few samples to adequately describe the variance across the island. Given the atypical Empirical Variogram result it may be a combination of factors. The ranges for the $\delta^{18}O$, δ^2H, $\delta^{13}C$, and $\delta^{34}S$ isotope ratios are 1.2, 19.7‰ (after removal of an outlier result), 2.1, and 6.6‰, respectively. The ranges of carbon, oxygen, and hydrogen stable isotope ratios are comparable to the ranges investigated in a multi-species review by Leavitt (2010). Kolombangara Island could be considered as a single "site" as the variation of the stable isotope data is in the natural range and there is no strong spatial structure evident at this time (**Figure 8**). However, the presence of the outlier could suggest the island may be considered as several sites, though the lack of spatial structure to the data does not strongly support this hypothesis. Further sampling of *Terminalia* in the region of the outlier sample may answer this question.

Vitex sp.

Though few samples of this genus were obtained and analysed, there are no significant differences in the $\delta^{18}O$, δ^2H, and $\delta^{13}C$ isotope ratios of *Vitex* sp. between Kolombangara and Guadalcanal Islands. Only the $\delta^{34}S$ isotope ratios show significant differences between the two origins, with the samples from Kolombangara showing significantly more enrichment in ^{34}S (Student's *T*-test $P < 0.05$) than the samples from Guadalcanal Island. This may be meaningful as other taxa sampled in this project did show significant differences in the $\delta^{18}O$, and δ^2H isotope ratios between the two islands (e.g., *Calophyllum* sp., *P. indicus*, and *T. grandis*).

DISCUSSION

Though some taxa have been minimally sampled, we believe it important to include their data so that others may have access to it for use in further dendroprovenancing research using stable isotope analysis. Sampling in tropical regions comes with many challenges, rain makes it hard to collect dry samples, biodiversity is high and important trees are often difficult to find (e.g., *P. indicus*), tropical wood is often dense, and it is hard to collect many samples in a short space of time. Despite all of this, a great many samples were collected overall, and we hope to build on their data over time throughout the WFID project with this piece of research laying the foundation for data, ideas, and improvements.

We believe that stable isotope data from *Campnosperma* and *Calophyllum* characterise Kolombangara Island well. *Eucalyptus* is characterised well-enough for evaluative purposes, but we are interested in gaining more samples from different parts of the island if *Eucalyptus* can be found in all areas of interest to further investigate the spatial trend that was observed. An *n* of 6 for *Terminalia*, given the outlier we observed, is close to the minimum for characterisation and it may be necessary to either explore the outlier sample more or eliminate it from the dataset. These findings are in keeping with guidelines from the Leavitt (2010) review which shows "*sampling 4–6 trees at a site while avoiding juvenile effects in rings near the pith*" is often sufficient for characterising site variability. However, the Leavitt (2010)

review considers stable isotope variation in sampling sites for the purposes of characterising tree-ring variability and can involve taking many more measurements per tree than in this research. The value of 4–6 trees at a site from studies used by Leavitt (2010) is based on using Expressed Population Signal (EPS) calculations which are prone to misinterpretation according to Buras (2017). EPS is often misunderstood to be a measure for the suitability of tree ring data for climate reconstruction, whereas according to Buras (2017, p. 2) "*In theory, EPS is the amount of variance of a population chronology (infinitely replicated) explained by a finite subsample.*" Therefore, it will be necessary to produce a more appropriate system for evaluating site variability and characterisation that is directly applicable to the methods presented in this research rather than rely on criteria outlined by Leavitt (2010).

Significant differences were found in numerous parameters of stable isotope data of multiple taxa between islands in the Solomon Islands (*Calophyllum* sp., *Pterocarpus* sp., *T. grandis*, and *Vitex* sp.). Though the overall quantities of each sampled taxa were relatively low, they were enough to establish ranges of values that can be used for the future evaluation of samples declared to have originated from the Solomon Islands. What is particularly promising is if the trend in the data collection continues, reliable island-level differentiation may be possible if more islands are sampled in the Solomon Islands archipelago. The results demonstrate that there is now a way to perform an evaluation to check whether a sample of FSC timber from the Solomon Islands (which must originate from Kolombangara Island) is from Kolombangara Island or not. Should a tested sample be inconsistent with data from Kolombangara Island, this could indicate that Kolombangara Island was not the origin of the timber and therefore should be subject to further scrutiny.
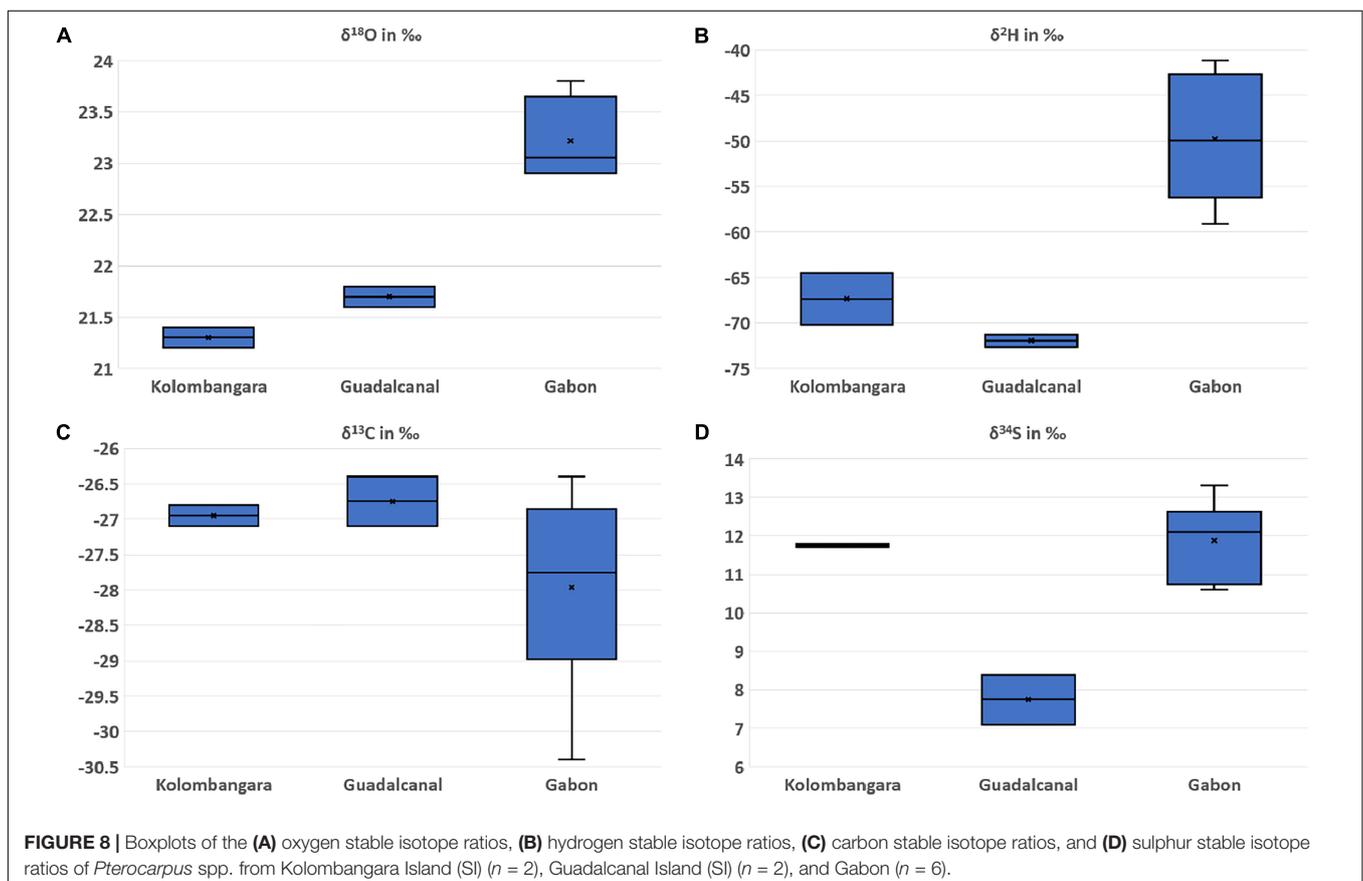
Differences in the ranges of stable isotope ratios were also evident in different taxa on the same site (assuming Kolombangara Island can be treated as a single site from a stable isotope perspective). On one hand this is disadvantageous because it highlights the necessity to sample as many different taxa as possible to defend any given origin and therefore will increase the cost of projects aimed at protecting the origin of taxa. On the other hand, four taxa (*Calophyllum* spp., *Pometia* sp., *Pterocarpus* spp., and *T. grandis*) show relationships in their $\delta^{18}O$ and δ^2H isotope ratios that can be compared to one another. To investigate this further, sampling 10 different taxa in the same site in 30 global locations would allow investigation into these relationships. A practical use of this information would be to establish a "Master" taxon for sampling that other taxa can be compared to in a model on a global scale.
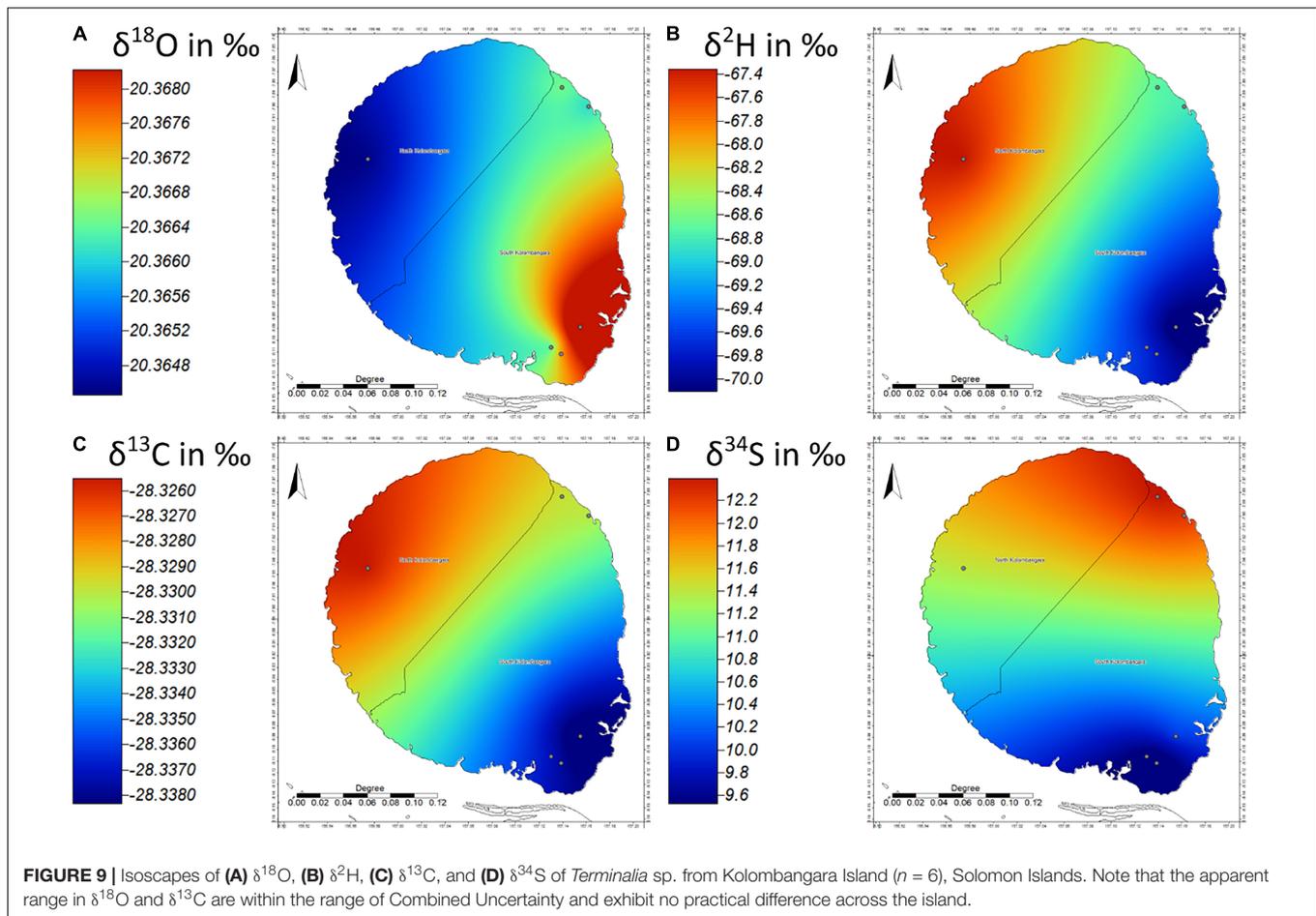
Though there is a wide range in the $\delta^{34}S$ of samples collected on Kolombangara Island (11‰) all samples were enriched in ^{34}S. The sulphur in the timber is expected to have originated from soil sulphur sources which in turn are expected to have originated from the volcano. Little has been published on the geology of the Solomon Islands, let alone Kolombangara Island save for "The British Solomon Islands Geological Record 1957 – 1958" (The Government of The British Solomon Islands, 1960) which reduces the ability for detailed interpretation of sulphur isotopes somewhat. Studies related to volcanic rocks have found

that volcanic rocks are enriched in ^{34}S relative to CDT (or VCDT) and ocean floor basalts (Sakai et al., 1982; Ueda and Sakai, 1984) which appears to be consistent with the findings from the Kolombangara Island samples.

Only one of the three investigated taxa (*Eucalyptus* sp.) showed any spatially predictable trends in variance within Kolombangara Island (**Figure 9**). While this is useful to make the case that a 30 km diameter area in the Solomon Islands can be considered as a single site for classification, the trends in *Eucalyptus* should be further investigated. It may be possible that the differences in *Eucalyptus* on the island can be explained by random chance, or it may be that a prevailing wind may influence the isotopic composition of precipitation even within such a small area. Climate reports for the island state that the northern side of the island is more sheltered whereas the southern side of the island is more exposed. Whitmore (1969) also documented that there is a "10 cm increase in rainfall for every 30 m increase in elevation up to 1500 m" on Kolombangara Island (likely meaning a 100 mm increase in annual rainfall for every 30 m increase in elevation). Gat et al. (2003) discusses that air-sea interactions near the coast in conditions where there is a deficit in humidity can result in a large deuterium-excess. It is possible that the gradient in wind and precipitation is responsible for the difference in stable isotopic composition of *Eucalyptus* sp. across the island. However, it is also worth considering that while the 25 samples of *C. brevipetiolatum* that were analysed did not show a spatially

predictable trend across the island, the pattern in δ^2H is similar across the island (**Figure 5B**) and may contribute to supporting the prevailing wind and precipitation hypothesis. This poses further questions, for example, why is the range in δ^2H only 13‰ for *Campnosperma* whereas it is 25.3‰ for *Eucalyptus*? Both woods are diffuse porous and can lack distinct growth ring boundaries. However, *C. brevipetiolatum* Volkens has 5–20 and 20–40 vessels/mm^2 whereas *E. deglupta* Blume has 5–20 vessels/mm^2 suggesting that water may move in greater rates in *C. brevipetiolatum*, though *E. deglupta* has vasicentric tracheids which conduct water albeit at lower rates. If the Peclet effect, the mixing of water from xylem and evaporative sites as a place for isotopic fractionation (Farquhar and Lloyd, 1993; Ferrio et al., 2011), is to be considered, these are important considerations for explaining differences in the isotopic composition of cellulose in the two types of tree. Given that there appear to be some differences in the ability of each tree to supply water to its leaves, this may explain some of the differences that have been observed. However, a greater difference between the trees appears to be in terms of the size of the leaves. *E. deglupta* leaves are approximately 7.5–20 cm long by 5.7–10 cm wide (Chippendale, 1972; Soerianegara and Lemmens, 1993), whereas *C. brevipetiolatum* leaves are much larger being over 30 cm long and up to 17.5 cm wide (Havel, 1963; Soerianegara and Lemmens, 1993). Perhaps the difference in size of the leaves also reflects that one is less susceptible to changing its stomatal conductance than

FIGURE 8 | Boxplots of the **(A)** oxygen stable isotope ratios, **(B)** hydrogen stable isotope ratios, **(C)** carbon stable isotope ratios, and **(D)** sulphur stable isotope ratios of *Pterocarpus* spp. from Kolombangara Island (SI) (*n* = 2), Guadalcanal Island (SI) (*n* = 2), and Gabon (*n* = 6).

FIGURE 9 | Isoscapes of **(A)** δ^{18}O, **(B)** δ^{2}H, **(C)** δ^{13}C, and **(D)** δ^{34}S of *Terminalia* sp. from Kolombangara Island (*n* = 6), Solomon Islands. Note that the apparent range in δ^{18}O and δ^{13}C are within the range of Combined Uncertainty and exhibit no practical difference across the island.

the other and may explain why one tree has a more homogenous isotopic composition than the other on the same island. Further investigation into this topic would yield results that may greatly inform how the differences in isotopic composition of different taxa can be calculated or considered.

The method of homogenising a core for analysis is appropriate to real-world testing of timber products. Homogenisation of multiple years of growth of a sample creates a robust mean value that is not heavily influenced by years that may have contained climatic anomalies (Leavitt, 2010). As all measured stable isotope ratios can be influenced by climate in some manner, this must be considered. A large proportion of the logs that are exported from the Solomon Islands to China are manufactured into plywood. As the veneers in plywood are created by rotary peeling of logs, a veneer sample subject to origin analysis may be influenced by climatic anomalies. However, as the data from the core reference sample represents this, the range of values in the reference samples should adequately cover this. However, one disadvantage to this approach appears to be that a degree of information is lost in the homogenisation of the sample and manifests only in terms of model uncertainty. δ^{13}C stable isotope ratios appear to be the most affected by this compromise; Kagawa and Leavitt (2010) demonstrated that high-level resolution of geographic origin assignment is achievable if multiple ring-widths of timber are

subject to δ^{13}C stable isotope ratio analysis. δ^{13}C stable isotope ratios are most significantly influenced by water-stress in C3 plants (Farquhar et al., 1989), therefore, building up a profile of years of variation in local climatic conditions related to water-stress can allow for excellent potential for origin assignment. Nevertheless, the disadvantage of this method is that one must know the year corresponding to the ring width of the test sample to make best use of this method for origin assignment. In plywood, or even sawn timber, the way to obtain this information does not seem obvious, hence the compromised utility of carbon isotope ratio analysis that is put forward in this project. The approach used here may be limited in some terms but is designed for practical use.

However, further work to validate the ability of these ranges to verify Kolombangara Island provenance is advisable. Good practice in data analysis often involves building datasets that are large enough to be partitioned into "training" and "test" sections so that an evaluative model can be constructed using the "training" dataset with its performance being assessed by techniques such as *k*-fold or leave one out cross validation (LOOCV), then subsequently validated using the "test" portion of the dataset. It may also be advisable to collect further samples of known origin and perform a "blind-test" evaluation. This case study has set out to establish a basis for evaluating origin claims

of timber from the Solomon Islands using stable isotope analysis and hopefully further work will permit validations of these sorts to be performed.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

FUNDING

ACKNOWLEDGMENTS

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2021. 645222/full#supplementary-material

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