

A framework for tracing timber following the Ukraine invasion

In the format provided by the
authors and unedited

1	Contents	
2	Section 1 Spatial scale analysis for verification	2
3	Section 2 Efficiency and coverage of 95% confidence region in determi-	
4	nation	2
5	Section 3 Descriptive analysis of stable isotope ratio and element varia-	
6	tion	4

7 Section 1 Spatial scale analysis for verification

8 We generated simulated harvest location claims in a way that facilitates direct
 9 comparison of results between spatial scales. For each incorrect claim of country
 10 origin, a location was chosen uniformly at random from within the country. We then
 11 identified the level-1 administrative region containing the location and used that as
 12 a region-level harvest location claim. We simulated concession-level harvest location
 13 claims by choosing, uniformly at random, a rectangular area of specified size that
 14 contained the sampled location. Two concession sizes were investigated: 0.5×0.5
 15 degrees and 0.25×0.25 degrees. For correct country origin claims, we chose region-
 16 and concession-level harvest location claims by applying the same procedure to the
 17 true location. In a second experiment, we limited location sampling for incorrect
 18 claims to those level-1 administrative regions that contained at least one training
 19 data point. This was done to investigate the impact of data availability near claimed
 20 locations on the sensitivity of the test.

21 The results are shown in Figure S1. The average sensitivity increases from 40%
 22 to 52% when level-1 units are used as declared harvest locations, rather than whole
 23 countries. For 0.25×0.25 degree concession harvest claims, the sensitivity increases
 24 to 60%. For samples from Russia, sensitivity was considerably higher at every spatial
 25 scale, ranging from 59% at country level to 82% at the concession level. This is
 26 accompanied by a slight decrease of specificity from 96% to 90% (see Figure S1).
 27 For samples from Belarus, the sensitivity ranged from 31% at country level to 51%
 28 at 0.5×0.5 concession level, with specificities between 100% and 85%. The incorrect
 29 harvest locations claims were more likely to be rejected if they were made in areas
 30 where training samples were available to our model - when incorrect claims were
 31 simulated only within level-1 units where at least one training sample has been
 32 collected, the sensitivity rose to 58% for level-1 declared locations, and 67% for
 33 0.25×0.25 degree concessions across all countries and reached 87% and 62% for
 34 samples from Russia and Belarus, respectively. This suggests that the accuracy of
 35 our verification test might be improved by collecting additional samples in areas
 36 where false harvest location claims are frequently made.

37 Section 2 Efficiency and coverage of 95% confidence 38 region in determination

39 We recall the definition of the posterior probability of a location $\mathbf{x} \in \mathcal{X}$:

$$Pr[\mathbf{x} | \mathbf{y}^*] = \frac{\mathcal{L}(\mathbf{y}^* | \mathbf{x}) Pr[\mathbf{x}]}{\sum_{\mathbf{x}' \in \mathcal{X}} \mathcal{L}(\mathbf{y}^* | \mathbf{x}') Pr[\mathbf{x}']}, \quad (1)$$

40 where the likelihood function is given by:

$$\mathcal{L}(\mathbf{y} | \mathbf{x}) = \prod_{j=1}^m \phi(y_j | \hat{\mu}_j(\mathbf{x}), \hat{\sigma}_j^2(\mathbf{x})),$$

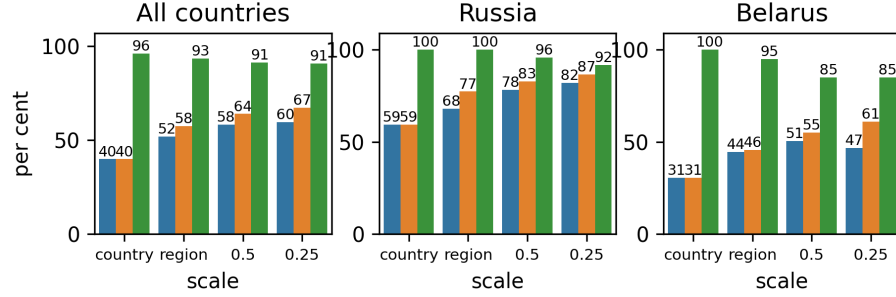


Figure S1: Accuracy at different spatial scales for the whole dataset, as well as for samples from Belarus and Russia. We report sensitivity for claims across each country (blue), sensitivity for claims within regions where samples are available (orange) and specificity (green) for four types of location claims: countrywide, regional (level-1 units), and simulated forest concessions of size 0.5x0.5 degrees and 0.25x0.25 degrees. More precise location claims result in improved sensitivity.

41 with $\phi(\cdot | a, b)$ the probability density function of a Gaussian distribution with mean
 42 a and variance b .

43 After calculating the posterior probability for every location in the study area $\mathcal{X}$,
 44 we report the predicted timber harvest location and the 95% confidence region for
 45 every test sample $\mathbf{y}^*$. The former corresponds to the location with highest posterior
 46 probability. The latter corresponds to the smallest set of locations whose posterior
 47 probability is at least 95% according to the model. Confidence regions are equivalent
 48 to credible regions in Bayesian statistics and correspond to regions within which the
 49 true location falls with 95% probability (**lee1989bayesian**). The interpretation is
 50 that there is a 95% probability that the true timber harvest location lies within the
 51 95% confidence region, given the evidence provided by the observed data. Note that
 52 the confidence region is constructed based on the posterior distribution in Eqn. 1
 53 and therefore depends on the prior $Pr[\mathbf{x}]$, the likelihood $\mathcal{L}(\mathbf{y}^* | \mathbf{x})$ of the observed
 54 data and model correctness.

55 To gain further insights in the 95% confidence regions, we have conducted
 56 additional experiments showcasing the *efficiency* and *coverage* of the predicted 95%
 57 confidence regions, obtained on the test samples. The former metric is expressed
 58 in km^2 and represents the average area of the 95% confidence regions. The latter
 59 metric reflects the proportion of test samples that encompass the true location. The
 60 results are presented in Table S1. In summary, the efficiency is given by 333006 km^2
 61 (approx. 577 km $\times$ 577 km), 230274 km^2 (approx. 480 km $\times$ 480 km), 429200
 62 km^2 (approx. 655 km $\times$ 655 km) and 274577 km^2 (approx. 524 km $\times$ 524 km), for
 63 *Betula*, *Fagus*, *Quercus* and *Pinus*, respectively. Note that the the total area of the
 64 study area, considered in this work, is approximately 5135505 km^2 . The coverage is
 65 given by 92%, 90.91%, 91.38% and 84.09%, for *Betula*, *Fagus*, *Quercus* and *Pinus*,
 66 respectively. In most cases, the coverage is close to the target confidence level of
 67 95%. However, it's crucial to emphasize that in real-world scenarios, the coverage

may deviate from the user-defined confidence level, due to the reasons that were outlined above: choice of prior, the observed data and model correctness.

Table S1: Efficiency and coverage for the 95% confidence regions obtained by different determination models on test data. We used the same test data, as outlined in the Experimental Setup in the main manuscript.

Genus	Efficiency (km ²)	Coverage
<i>Betula</i>	333006	92.00%
<i>Fagus</i>	230274	90.91%
<i>Quercus</i>	429200	91.38%
<i>Pinus</i>	274577	84.09%

70

Section 3 Descriptive analysis of stable isotope ratio and element variation

In an additional set of experiments, we investigate the total and local variation of stable isotope ratios and trace elements, given the observed data for *Betula*, *Fagus*, *Pinus* and *Quercus*. The results are presented in Fig. S2, S3, S4 and S5, respectively. For the sake of space, based on insights from **boeschoten2022clay**, **Rees2015** and the feature importance insights from the SHAP analysis, the following subset of the stable isotope ratios and trace elements are chosen: $\delta^2\text{H}$, $\delta^2\text{H}_{nit}$, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{18}\text{O}$, $\delta^{34}\text{S}$, Ca, Cl, Cu, Fe, Ni, Pb, Sr and Zn.

We generate boxplots to assess the total versus local variability of the subset of stable isotope ratios and trace elements for each genus. In each plot, the left panel presents the total variation, i.e., encompassing all available data, while the right panel presents local variations specific to each country. To analyze local variations, we use 4-means clustering based on the Euclidean distance, categorizing test samples into four distinct clusters. Each cluster contains samples that are closely located in space. Expanding the number of clusters enhances our understanding of the local variation in specific stable isotopes or trace elements within a particular country.

The following main trends are observed: 1) local variations tend to be notably smaller than total variations, and 2) in most cases, a substantial difference in average stable isotope and trace element values exists between different countries and clusters within countries. This illustrates that the majority of stable isotope ratios and trace elements contain sufficient spatial information for most genera.



Figure S2: Total and local variation for different stable isotopes and trace elements in *Betula*. Stable isotopes ($\delta^2\text{H}$, $\delta^2\text{H}_{nit}$, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$) and trace elements (Ca, Cl, Cu, Fe, Ni, Pb, Sr and Zn) are considered. Local variation is plotted by means of boxplots for four distinct clusters, obtained by 4-means clustering and the Euclidean distance, in each country. Total variation is plotted by means of a boxplot for all data. The boxplots show the median and 25th and 75th percentiles of the data, with whiskers extending to 1.5 times the interquartile range. Sample sizes for the boxplots are presented in Table S2.

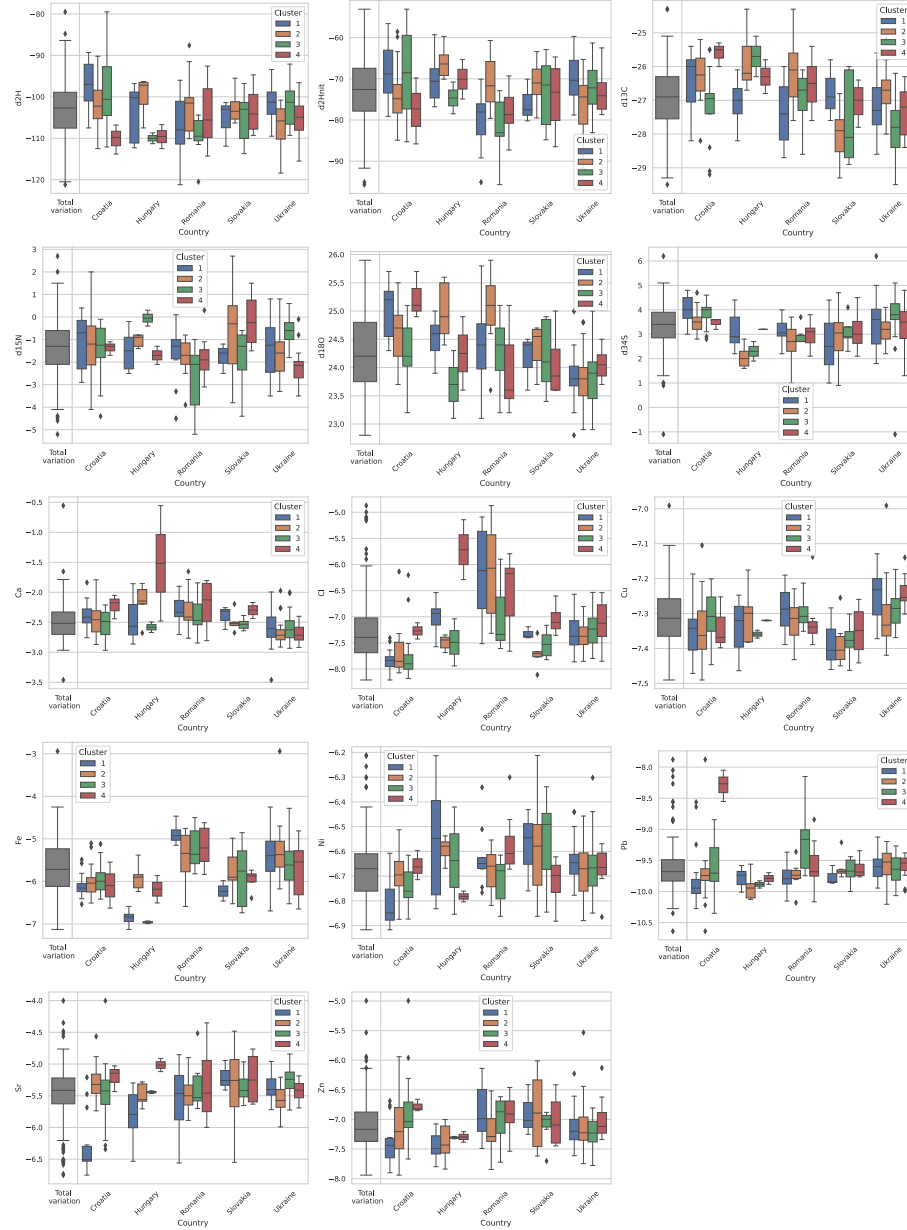


Figure S3: Total and local variation for different stable isotopes and trace elements in *Fagus*. Stable isotopes ($\delta^2\text{H}$, $\delta^2\text{H}_{\text{nit}}$, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$) and trace elements (Ca, Cl, Cu, Fe, Ni, Pb, Sr and Zn) are considered. Local variation is plotted by means of boxplots for four distinct clusters, obtained by 4-means clustering and the Euclidean distance, in each country. Total variation is plotted by means of a boxplot for all data. The boxplots show the median and 25th and 75th percentiles of the data, with whiskers extending to 1.5 times the interquartile range. Sample sizes for the boxplots are presented in Table S2.



Figure S4: Total and local variation for different stable isotopes and trace elements in *Pinus*. Stable isotopes ($\delta^2\text{H}$, $\delta^2\text{H}_{nit}$, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$) and trace elements (Ca, Cl, Cu, Fe, Ni, Pb, Sr and Zn) are considered. Local variation is plotted by means of boxplots for four distinct clusters, obtained by 4-means clustering and the Euclidean distance, in each country. Total variation is plotted by means of a boxplot for all data. The boxplots show the median and 25th and 75th percentiles of the data, with whiskers extending to 1.5 times the interquartile range. Sample sizes for the boxplots are presented in Table S2.



Figure S5: Total and local variation for different stable isotopes and trace elements in *Quercus*. Stable isotopes ($\delta^2\text{H}$, $\delta^2\text{H}_{\text{nit}}$, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$) and trace elements (Ca, Cl, Cu, Fe, Ni, Pb, Sr and Zn) are considered. Local variation is plotted by means of boxplots for four distinct clusters, obtained by 4-means clustering and the Euclidean distance, in each country. Total variation is plotted by means of a boxplot for all data. The boxplots show the median and 25th and 75th percentiles of the data, with whiskers extending to 1.5 times the interquartile range. Sample sizes for the boxplots are presented in Table S2.

Table S2: Sample sizes for descriptive analysis of stable isotope ratio and element variation. For each country and genus, we show the sample sizes for the four clusters.

Genus	<i>Betula</i>				<i>Fagus</i>				<i>Pinus</i>				<i>Quercus</i>			
Belarus	6	6	4	4	0	0	0	0	0	0	0	0	4	3	1	2
Croatia	3	5	9	3	15	24	18	3	4	12	9	5	9	11	27	10
Estonia	12	13	18	7	0	0	0	0	0	0	0	0	2	3	3	2
Finland	7	8	9	6	0	0	0	0	8	11	7	10	0	0	0	0
Hungary	2	1	1	6	7	5	2	2	4	4	4	1	11	15	12	11
Latvia	15	12	17	12	0	0	0	0	0	0	0	0	1	1	1	1
Lithuania	0	0	0	0	0	0	0	0	15	21	13	16	8	6	12	8
Moldova	0	0	0	0	0	0	0	0	0	0	0	0	18	12	15	6
Romania	3	1	5	3	10	11	7	7	0	0	0	0	3	3	2	2
Russia	9	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0
Slovakia	6	3	6	5	3	6	7	4	0	0	0	0	1	3	3	2
Ukraine	6	21	15	18	28	21	27	12	9	3	12	6	0	0	0	0