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Economic valuation of illegal Brazilian Amazon deforestation: A framework based on Habitat Equivalency Analysis and ecosystem services restoration

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ABSTRACT

This work introduces a framework for assessing the economic value of illegal clearings in the Amazon primary rainforest based on Habitat Equivalency Analysis and the restoration of suppressed ecosystem services (ES). The framework ensures ES restoration in both quantity and quality, considering past and current losses as well as future gains adjusted for discount rates to present values. The translation of ES restoration into economic values is grounded in local market values, striving to ensure the results are both representative and accurate. The application of the framework in 10 ha of illegally cleared Amazon primary rainforest resulted in an economic valuation of 2022 Int.$ 341,611, or 2022 Int.$ 3175 per hectare per year, which is 35 % higher than valuations based solely on timber and cleared area restoration. The framework is sensitive to compensation period, discount rate, and ES recovery curve, leading to economic effects on the valuation of the illegal clearings in the Amazon primary rainforest. The framework is distinguished by its low human, material, and temporal costs, making it applicable even in preliminary environmental assessments. By describing the tangible economic value of Amazon primary rainforest illegal clearings, the framework allows for critical comparison with existing literature on tropical forest values, aiming to enrich society's comprehension of the costs and benefits of Amazon deforestation.

1. Introduction

Illegal deforestation presents a critical issue in the Brazilian Legal Amazon, affecting both private and public lands. Addressing illegal deforestation on private lands involves holding landowners accountable for fines and environmental compensation. However, identifying responsible parties on public lands poses significant challenges. Illegal deforestation on public lands is intertwined with the illicit conversion of these lands into private property, involving squatters, land grabbers, property title distribution, and notaries [15]. This process subsequently makes the "privatized" land available for real estate transactions and economic activities. Such activities exert a significant impact on local economic and political dynamics, fueling a deforestation cycle that drives the expansion of the agropastoral frontier.

The economic valuation of tropical forests plays a pivotal role in this deforestation cycle. Undervaluing the current and future ecosystem services (ES) provided by tropical forests encourages their conversion into unproductive pastures and croplands, resulting in ephemeral socio-economic impacts and long-lasting damaged areas. Furthermore, undervaluing ES inhibits forest protection for payments for ecosystem

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Abbreviations: BRL, Brazilian currency (Real); ES, ecosystem services; ha, hectare; HEA, Habitat Equivalency Analysis; Int.$, international dollar; NOAA, National Oceanic and Atmospheric Administration; OGF, old-growth forest; PES, payment for ecosystem services; PPV, purchasing power parities; PVM, present value multiplier; TEEB, The Economics of Ecosystems and Biodiversity; ESVD, Ecosystem Services Valuation Database.

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services (PES). The basis of PES is to account for all values of ES, compensating forest managers for optimizing the forest's ES rather than pursuing purely exploitative paths [2].

Therefore, a comprehensive assessment of various ES can justify the importance of conservation mechanisms, especially in developing countries where forests significantly contribute to sustaining community livelihoods [1,19,21,30]. Underestimating the economic value of ES misleads society regarding the actual cost-benefit analysis of depleting natural resources. Increasing awareness about the social and environmental costs linked to deforestation makes it challenging to develop unproductive economic activities in cleared areas, consequently hindering the incorporation of public lands into the agrosilvopastoral frontier.

Efforts to compile the economic values of tropical forests, based on the aggregation of economic values attributed to different ES,[1] have been presented by several authors. Costanza et al. [6] estimated the mean economic value of the tropical forest in 1994 as US$ 2007/ha/year, while Torras [27] assessed the economic value of the Amazon forest at US$ 1175/ha/year. de Groot et al. [7] recalculated the economic values of tropical forest ES in 2007 as Int.$ 5264/ha/year (mean). Taye et al. [25] described the mean economic values of tropical rainforest and primary forests in 2017 as US$ 1747/ha/year and US$ 3034/ha/year, respectively.

Considering the studies mentioned above, inflation-adjusted mean economic values of tropical forests range from 2023 Int.$ 2073 to 7695/ha/year. An even greater dispersion of economic values for tropical forests is observed within the mentioned meta-analysis studies. de Groot et al. [7] delineated the economic values for tropical forests, spanning from 2007 Int.$ 1581 to 20,851/ha/year, with mean and median values reported as 2007 Int.$ 5264/ha/year and 2007 Int.$ 2355/ha/year, respectively. Taye et al. [25] detailed the economic values of tropical rainforests, indicating a mean of 2017 US$ 1747/ha/year and a median of 2017 US$ 113/ha/year. Additionally, the economic values for primary natural forests were reported as 2017 US$ 3034/ha/year (mean) and 2017 US$ 139/ha/year (median). The mentioned studies report positively skewed distributions, with medians significantly lower than the mean values described, indicating a substantial concentration of economic valuations around the median and a few valuations extending well above it.

Several factors may contribute to the large dispersion of economic values in tropical forests. Meta-analysis studies are based on primary data generated in different countries with diverse cultures and economic contexts, obtained through various methods of ES valuation and considering a specific number of ES for determining the economic value of the tropical forest. As observed by Taye et al. [25], the values of ES have considerable variations across countries and regions, with essential variables significantly affecting the economic value of forest ES, such as GDP per capita, population density, forest cover, continental location, forest types, protection status, and valuation approaches.

Considering the dispersion of economic values of tropical forests in the literature, forest protection activists ground their position on utilizing the highest limits of the economic valuation of tropical forests. They advocate that conversion should only be allowed if the socio-economic benefits significantly surpass these values. Conversely, proponents of forest conversion base their perspectives on the low economic values attributed to the forest, arguing that many activities can generate socio-economic benefits exceeding these more modest values. However, selecting representative economic values for ES requires a preliminary examination of the spatial scale and assessing the precision and accuracy involved.

As observed by Kubiszewski et al. [14], the range of uses of ES economic values includes rising social awareness, national income and well-being accounts, specific policy analysis, urban and regional land use planning, and PES, with spatial scale varying from regional, national, and global. Additionally, a broad range of economic valuation methods for ES[2] are described in the literature, providing different levels of precision and accuracy, and requiring a range of financial, time, and personnel resources. Understanding the trade-offs between the study's costs and the result's precision is essential to support its application.

The representativeness of the sample distribution is commonly questioned for the use of literature's economic valuation data for tropical forests within the Brazilian Legal Amazon. For instance, in determining the average economic value of the tropical forest, Costanza et al. [6] relied on 24 studies conducted in 15 countries, with only one study conducted in Brazil. The economic values of the tropical forest defined by de Groot et al. [7] were based on 23 studies conducted in 16 countries, with no studies conducted in Brazil. Taye et al. [25] considered 261 studies to determine the economic values of tropical forests without indicating the number of studies conducted in Brazil.

A current overview of the economic valuation of Brazilian tropical forests is available in the Ecosystem Services Valuation Database (ESVD) [3] [4] and is presented in Box 1.

Box 1 illustrates how average economic values of tropical forests have been defined. It is shown that many classes of tropical forest ES have not been valued, and some classes of tropical forest ES have a low number of studies. The significant variation of economic values assigned to the same ES results in a wide range of economic values for the tropical forest.

Without prior local tropical forest economic valuation, environmental assessments tend to adopt average literature values as a conservative valuation. Although it cannot be considered a value (benefit) transfer, it gives a provisional value while future studies, which will depend on cost, time, and personnel availability, define a more specific local economic valuation. Thus, the greater the tropical forest value dispersion in the literature, the more questionable the average value adopted for an unvalued tropical forest area.

Illegal deforestation violates existing rules concerning protected species, maximum permitted wood volumes, and other principles of sustainable forest management. Therefore, any products derived from illegal deforestation (e.g., timber) or produced on illegally cleared land should not be accounted for as potential benefits of illegal deforestation. Such accounting would undermine the legal deforestation system and distort the market value of legally harvested timber and goods produced on legally deforested land. Considering that illegally deforested areas have lower costs and greater incomes for extracting forest products and establishing pastures and crops than legalized areas, these activities unfairly compete with legalized producers and somehow reward predatory exploitation at the expense of sustainability.

When avoiding using average values from the literature, preliminary assessments of environmental damages resulting from illegal deforestation in the Brazilian Legal Amazon typically focus on restoration costs and the value of extracted timber. Interim losses, or the ES not provided by tropical forests between clearing and complete forest restoration, are rarely assessed. Consequently, these evaluations often convey an underestimated value of the tropical forest, sending a misleading

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[1] For instance, Costanza et al. [6] considered in their paper the economic values of the following ES: gas regulation, climate regulation, disturbance regulation, water regulation, water supply, erosion control and sediment retention, soil formation, nutrient cycling, waste treatment, pollination, biological control, refugia, food production, raw materials, genetic resources, recreation and cultural.

[2] The valuation methods include Avoided Costs, Choice Modelling, Contingent Valuation (Willingness-To-Pay), Energy Analysis, Group Valuation, Hedonic Pricing, Input-Output Modelling, Life Satisfaction, Marginal Product Estimation, Market Value/Price (Gross Revenue), Production Function, Replacement Cost, Simulation Modelling, Travel Costs and Value (Benefit) Transfer.

[3] https://www.esvd.net/esvd accessed on 02/01/2024.

Box 1

Current situation of Brazilian tropical forests in ESVD.

A search in ESVD considering Biome: "Tropical and subtropical forests" and Country: "Brazil," returns 340 studies. These studies present economic valuations of Brazilian tropical and subtropical forests produced by the following valuation methods (number of studies in parentheses): Choice modelling (1), Contingent valuation (66), Damage cost avoided (29), Group valuation (8), Market prices (33), Net factor income (7), Opportunity cost (10), Production function (138), Public pricing (6), Replacement cost (12), Restoration cost (10), Social cost of carbon (15), Value (benefits) transfer (38) and Other (23). Out of these studies, 94 valuations considering nine classifications of ES by The Economics of Ecosystems & Biodiversity (TEBB) were selected by the following rules (Box 1 Table): i) Could be standardised to a common set of units (International dollars/hectare/year in 2020 price levels); ii) Refer to only one biome and one ecosystem service and iii) Do not use value transfer as a valuation method.

Box 1 Table

Economic values of ES provided by Brazilian tropical and subtropical forests.

TEEB services classification	Number of Valuations	2020 Int.$/ha/year			
		Minimum	Maximum	Mean	Median
1. Food	2	2.69	5.38	4.03	4.03
3. Raw material	18	0.60	6650.00	773.00	15.00
4. Genetic resources	4	273.00	846.00	508.00	457.00
8. Climate regulation	5	53.00	3057.00	1225.00	227.00
9. Moderation of extreme events	1	42.00	42.00	42.00	42.00
10. Regulation of water flows	6	0.34	49.00	11.00	3.60
14. Pollination	54	0.00	2821.00	245.00	16.00
19. Opportunities for recreation and tourism	1	0.09	0.09	0.09	0.09
23. Existence, bequest values	3	12.00	254.00	118.00	87.00
Total	**94**	**383.72**	**13,724.47**	**2926.12**	**851.72**

Box 1 Table indicates that the economic value of the Brazilian tropical and subtropical forest ranges from 2020 Int.$ 383–13,724/ha/year, with a mean and median of 2020 Int.$ 2926/ha/year and 2020 Int.$ 851/ha/year, respectively.

ES can be classified in 23 TEBB services classification. There is no economic valuation of Brazilian tropical and subtropical forests ES in the following TEBB services classification: 2. Water, 5. Medicinal resources, 6. Ornamental resources, 7. Air quality regulation, 11. Waste treatment, 12. Erosion prevention, 13. Maintenance of soil fertility, 15. Biological control, 16. Maintenance of life cycles, 17. Maintenance of genetic diversity, 18. Aesthetic information, 20. Inspiration for culture, art and design, 21. Spiritual experience, 22. Information for cognitive development.

ESVD does not advise using the statistics presented in Box 1 Table for value transfers since the “statistics reflect the underlying ecological and socio-economic contexts of diverse (but not necessarily representative) study sites."

message to society regarding its true significance.

This work introduces a framework for assessing the economic value of illegal clearings in Amazon rainforest based on Habitat Equivalency Analysis (HEA) and the restoration of the suppressed ES. The framework ensures ES restoration in quantity and quality, considering past and current losses and future gains adjusted for discount rates to present values. The translation of ES restoration into economic values is grounded in local market values, aiming to ensure the results are both representative and accurate. The framework is distinguished by its low human, material, and temporal costs, making it applicable even in preliminary assessments. Its application seeks to improve the communication of the value of tropical forests to society, thereby contributing to the mitigation of illegal deforestation.

2. Conceptual basis of HEA

King and Adler [13] explored the concept of compensation rates, or the relationship between the area of ecosystem restored needed per area of ecosystem lost, further developed by Unsworth and Bishop [28], with restoration seen as resource-based compensation. NOAA [16] developed HEA as a way of measuring compensation for habitat damage, providing complete in-species replacement (i.e., of similar quality and quantity) of ES lost from the time the environmental damage occurred until the services have been restored or created at their full replacement value. It is a service-to-service or resource-to-resource approach to natural resource assessment that estimates temporary losses to ES for compensatory restoration purposes.

HEA scales the extent of restoration so that the total gains from services provided at a compensation location equal the losses in services. HEA assesses restoration options using ecological rather than economic inputs, estimating the amount of restoration efforts sufficient to compensate society for losses resulting from damage [23]. Based on the extent and expected duration of damage to resources and the predicted trajectory of increases in ecological services over time due to restoration, losses (debits) and gains (credits) in services are estimated [16].

HEA seeks to estimate the ecological value of lost resource services by determining the amount of resources/habitat that must be provided to compensate for any loss (known as restoration or compensatory remediation) without requiring the need to assign value money to services [9]. Intended for use when service losses are primarily ecological [8], the main assumption of HEA is that the per-unit economic value of remediation actions is equal to the per-unit value of the damaged resource or service. Ensuring that the scale of remediation adequately compensates the public for the damage caused [10] allows the cost of environmental damage to be calculated based on the costs of primary remediation (i.e., processes implemented in the damaged area aiming to restore its original condition) and compensatory remediation (i.e., processes aiming to compensate interim loss calculated during damage area restoration) actions.

The HEA structure involves three basic steps: 1. Establish the baseline and assess the present value of lost services; 2. Select appropriate restoration/mitigation compensatory measures; 3. Calculate the compensation that equates the total discounted amount of lost services to the total discounted amount of replacement services.

The baseline refers to the condition of natural resources and services that would have existed if the incident had not occurred. Establishing the baseline requires defining the level of habitat, resources and ES before damage and, consequently, the level of recovery to be achieved after natural recovery or primary and complementary remediation projects. Baselines are important for establishing liability, properly defining restoration endpoints, and estimating damage [12].

Interim losses, or the losses of ES caused by environmental damage (departing from the baseline) until the return of the ES supply after the damage is recovered (return to baseline), assumes that the amount of ES that is no longer being supplied due to environmental damage can only be compensated by an extra supply of ES. Such compensation is called compensatory remediation and may involve the enhancement or creation of resources. As losses and gains occur in different years and remain in the future, a discount rate is applied to translate all amounts of ES into their current year value. The discount rate reflects the social rate of time preference, that is, society's willingness to change the "consumption" of public goods (such as natural resource services) over time [9].

Based on the discount rate, a present value multiplier (PVM) [10], also called discount factor [16], is calculated by Eq. 1.

$$PVM = \frac{1}{(1+r)^{(year-base\ year)}} \tag{1}$$

where:

r = discount rate;

year = year when losses or gains occur;

base year = year used for the present value calculations.

Eq. 1 shows that for losses and gains in the future, where year > base year, PVM acts as a discount factor (PVM < 1). For losses in the past, where year < base year, PVM acts as a compound factor (PVM > 1). HEA applies PVM to the biophysical amount of ES [22] and allows the updating of past environmental damage and the pricing of future losses and gains of ES [10].

The amount of ES to be compensated is calculated based on when the damage occurred; when restoration begins; how many years losses occur; how many years gains are made (at a replacement site, for example); total services sacrificed of one hectare of the damaged ecosystem; the level of ES lost; the expected ES of the restored ecosystem; and when the ecosystem returns to baseline conditions. As it is expensive and difficult to measure all components of an ecosystem, HEA relies on the use of an indicator to measure the level of ES lost through deforestation and gained through compensation. Generally, the best indicator is an ecological parameter representative of damaged habitats and/or natural resources. This indicator is central to the process, as it will be used both to determine losses resulting from damage and to measure the gain associated with compensatory remediation [22,24,29].

3. Illegal clearing valuation framework

The framework presented in this study considers that after illegal deforestation, individual ES in all 23 TEBB classes[4] stopped being provided. The framework starts calculating the interim loss, or the bundle of the Amazon primary rainforest ES suppressed by illegal deforestation, from clearing until the complete forest recovery under the primary remediation process. The amount of Amazon primary rainforest ES not delivered during primary remediation must be provided during the compensatory remediation process. The framework determines the size of a forest restoration area to produce ES to offset interim losses. Instead of focusing on the individual ES provided by the Amazon primary rainforest, the framework relies on primary and compensatory remediation processes, where assisted forest restoration projects will deliver ES in the same quality and quantity as those suppressed by illegal deforestation.

Fig. 1 illustrates[5] the illegal conversion of 10.00 ha of Amazon primary rainforest[6] to pasture and the framework's primary and compensatory remediations.

All results presented in the following sections are detailed in the Supplementary Information (Figures and Tables "S").

3.1. Assisted Amazon rainforest restoration

The framework considers that illegally cleared areas must be restored through a primary remediation process applying assisted Amazon rainforest restoration.[7]

The percentage of ES provided by the area under recovery is considered proportional to the average percentage of recovery of the attributes of old-growth secondary forest (OGF) during forest restoration: areas recently cleared and pastures provide 10 % of the ES of the OGF; climax forest before damage or after full recovery provides 100 % of ES.

The forest restoration curve was based on the work of Poorter et al. [20], which monitored 12 forest attributes[8] during secondary forest succession. Poorter et al. showed that forest attributes in abandoned lands (under natural recovery) attain 78 % (median) of their old-growth values after 20 years (or ~87 % in 40 years). Considering that the

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[4] 1 Food provision, 2 Water provision, 3 Fuels and fibres, 4 Genetic resources, 5 Medicinal and other biochemical resources, 6 Ornamental resources, 7 Air quality regulation, 8 Climate regulation, 9 Moderation of extreme events, 10 regulation of water flows, 11 water purification, 12 Erosion prevention, 13 Maintenance of soil quality, 14 Pollination services, 15 Biological control, 16 Maintenance of life cycles of migratory species, 17 Maintenance of genetic diversity, 18 aesthetic information, 19 opportunities for recreation and tourism, 20 inspiration for culture, art and design, 21 spiritual experience, 22 information for cognitive development and 23 existence, bequest values.

[5] Source: Programa Brasil MAIS (https://plataforma-pf.sccon.com.br/#/), includes material © (year) Planet Labs Inc. All rights reserved.

[6] As in [11], primary forests are defined as a naturally regenerated forest of native species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed.

[7] Including access restriction to the restoration area, planting of Amazonian forest species with a 3×2 m spacing (1666 seedlings/ha), and compliance with a minimum schedule of three years of cultural practices, such as fertilization, control of leaf-cutting ants, application of pesticides, replanting and irrigation.

[8] Soil bulk density, soil carbon, soil nitrogen, community nitrogen fixers, wood density, specific leaf area, aboveground biomass, maximum tree diameter, structural heterogeneity, species richness, Simpson diversity and species composition.

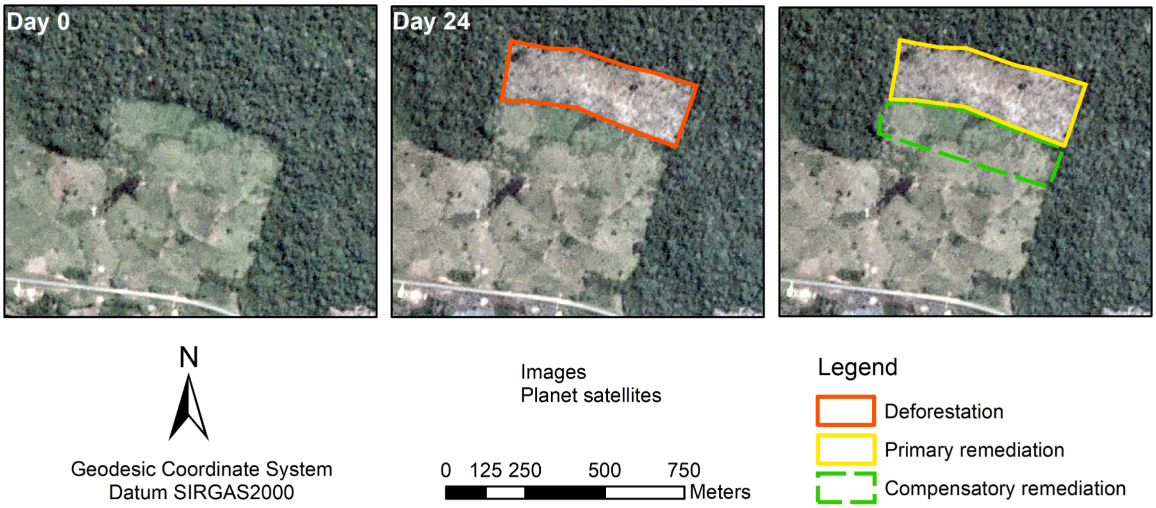

Fig. 1. The illegal conversion of Amazon primary rainforest to pasture in 24 days (10.00 ha deforestation – red line). Forest restoration project on-site recovers the cleared area (10.00 ha primary remediation – yellow line). Forest restoration project off-site (adjacent pasture) offsets the interim losses (8.05 ha compensatory remediation – green dashed line).

Table 1
Interim losses parameters.

Parameters	Values
Damaged area	10.00 ha
ES after clearing/pasture (%ES$_{initial}$)	10 %
Baseline: considering ES OGF (%ES$_{final}$)	100 %
Recovery curve	Eq. 2
Discount rate	3 %
Base year	2023
Recovery time	40 years

framework is based on assisted forest restoration, it is reasonable to assume that forest attributes will be recovered faster than under natural recovery, ensuring that 90 % of recovery can be achieved in 40 years[9] and consequently returning to supply 90 % of the forest's ES. Due to the asymptotic behaviour of the forest restoration curve, pointing to 100 % at infinity, and because of the natural variation in the ES OGF level at approximately 100 %, the recovery of 90 % of the forest's ES was considered the endpoint for forest restoration. The Amazon rainforest restoration curve, also considered the ES recovery curve, is presented in Table S1, Figure S1 and Eq. 2.

$$\%ES_t = \%ES_{initial} + (\%ES_{final} - \%ES_{initial}) \times (1 - e^{-\lambda t}) \tag{2}$$

where:

$\%ES_t$ = percentage of ecosystem services provided in time t (t in years) after implementation of a forest restoration project;

$\%ES_{initial}$ = percentage of ecosystem services provided before the start of the forest restoration project. Clearings and pastures provide 10 % of the ecosystem services of the original Amazon primary rainforest;

$\%ES_{final}$ = percentage of ecosystem services provided by the original Amazon primary rainforest: 100 %; and

λ = relative recovery rate: for $\%ES_{40\ years} = 90\ \%$; $\lambda = 0.055$.

The assisted Amazon rainforest restoration model applied to the framework incorporates variables such as species richness and composition and aboveground biomass, which are related to many ES that may impact the tropical forest value. The framework evaluates aggregated ES rather than assessing marginal changes in specific ES.

3.2. *Interim losses quantification*

The interim losses are quantified from the annual debits calculation during primary remediation. Annual debits are calculated by multiplying the damaged area, the percentage loss of ES (compared to baseline) and the PVM. The sum of the annual debits gives the value of the interim losses. The interim losses of the 10.00 ha of forest clearing in 2023 until its restoration in 2063 after primary remediation were calculated as 107.53 ES x ha. Table 1 shows the parameters used during the interim loss calculation. Table S2 shows the interim losses calculation, and Figure S2 presents the interim losses graphic illustration.

3.3. *Compensatory remediation area*

As outlined in Section 3.1, Amazon primary rainforests (climax) provide the maximum amount of ES per area (100 %). Therefore, a successful restoration project in a deforested area will ideally return the ES supply to 100 %. To compensate for interim losses, additional ES must be generated through compensatory remediation off-site, increasing the ES supply near the cleared area, such as in adjacent pastures.

According to Table 1, the amount of ES per year produced by forest restoration on 1 ha of pasture was calculated by multiplying the percentage of ES supplied (compared to the baseline) and the PVM. The sum of annual credits is the total value of ES generated by the assisted forest restoration project on 1 ha. Table S3 and Figure S3 depict the evolution of credits in ES provided by assisted forest restoration on 1 ha.

Figure S3 illustrates the assisted forest restoration on 1 ha of pasture, yielding 90 % ES OGF after 40 years, resulting in the production of 13.36 ES. Dividing the interim loss (107.53 ES x ha) by 13.36 ES yields 8.05 ha, which is the extent of the compensatory remediation area. Figure S4 provides a graphical representation of compensatory remediation.

The framework involves three basic steps, as presented in Section 2:

1. Establish the baseline and assess the present value of lost services: The baseline, as described in Section 3.1, is the ES supply from Amazon primary rainforests, initially providing 100 % of the

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[9] Although the recoveries of some forest attributes in Poorter's study present a wide range of 95 % credible intervals, assisted forest restoration tends to accelerate forest recovery and narrow credible intervals, supporting the HEA deforestation framework valuation to be considered as minimum Amazon primary forest value.

baseline value before clearing. Cleared areas or pastures offer only 10 % of the baseline, with ES provision increasing during primary remediation, asymptotically approaching 100 % of the baseline and reaching 90 % after 40 years;

2. Select appropriate restoration/mitigation compensatory measures: The proper compensatory measure involves assisted forest restoration in two different areas: the primary and compensatory remediation areas (on and off-site, respectively), as outlined in Section 3.1;
3. Calculate the compensation equating the total discounted amount of lost services to the total discounted amount of replacement services: As detailed in Sections 3.2 and 3.3, a primary remediation project in the cleared area results in interim losses of 107.53 ES x ha over 40 years, necessitating compensatory remediation in 8.05 ha to offset these losses.

Fig. 2 illustrates the interim losses, compensatory remediation, and net flux of suppressed and provided ES (in ES x ha) until year 2100, considering deforestation occurring in 2023 and primary and compensatory remediations commencing in the same year. Fig. 2a depicts the interim losses calculation from the clearing date to 40 years ahead, when primary remediation will restore the baseline to 90 % of the OGF. Fig. 2b shows compensatory remediation conducted in 8.05 ha, producing 107.53 ES x ha over 40 years to offset interim losses. Fig. 2c illustrates the net flux of ES, measured in ES x ha, from 2023 to 2100, indicating a positive trend starting in 2063, growing at a diminishing rate each year and reaching ~50 ES x ha in the long run.

A positive value of ES x ha in the long run is crucial for interim losses compensation in the short run (here, 40 years). Any deficiencies in compensation during forest restoration (e.g., drought, rain, fire, soil extenuation, animals) might be rectified by extending the 40-year period. If interim losses compensation is successful, the compensatory remediation area may be repurposed for other uses, including clearing. However, if discount rates greater than 3 % are applied, ES x ha values will diminish in the long run, as demonstrated in the Supplementary Information – Framework sensitivities.

In a strictly compensatory manner, the smallest compensatory remediation area is defined by the lowest ES x ha value in the long run. Figure S5 displays the net flux of ES for interim losses compensation of 10.00 ha of Amazon primary rainforest over 80 years, with a compensatory remediation area of 5.51 ha. Considering a generation period of 25 years, such compensation would extend over a period longer than three generations, effectively immobilizing land use for the same duration, with any deficiencies in compensation due to forest restoration evolution being less circumventable.

Compensatory remediation allows for flexibility in handling by defendants, who may: 1) develop a compensatory remediation project on their property; 2) acquire surrounding areas for the project; or 3) finance the project's costs, managed by trustees and environmental agencies, focusing restoration activities on ecological corridors or priority restoration/conservation areas. After 40 years of compensatory remediation, interim losses are considered offset. Although it's challenging to predict economic activities allowed in compensatory remediation areas 40 years ahead, timber exploitation under sustainable management could potentially provide financial benefits post-remediation.

3.4. *Economic valuation*

The economic valuation of illegally cleared Amazon primary rainforest considered the following steps: 1) assessing the direct use value of the timber extracted from the deforested area; 2) implementing a forest restoration project under primary remediation for the cleared area; 3) factoring in the cost of land acquisition for compensatory remediation; and 4) executing a forest restoration project in the compensatory remediation area.

All values shown have been standardized to 2022 International Dollars (2022 Int.$). Monetary values described in Brazilian currency (BRL) were adjusted for Brazilian inflation (up to 05/2023 – IPCA/IBGE) and converted to international dollars using the Purchasing Power Parities (PPP) conversion factor (2022 Int.$1.00 = 2,530BRL).[10]

The timber productivity ranged from 40.043 to 146.415 m^3/ha (mean value: 90.037 m^3/ha).[11] Updated timber commercial values varied from 2022 Int.$ 134–263/m^3 (mean value: 2022 Int.$ 186/m^3)[12,13]. Thus, the timber extracted by 10.00 ha of deforestation was valued in 2022 Int.$ 167,468.

The updated cost of assisted forest restoration projects ranged from 2022 Int.$ 3677 to 14,609/ha[14,15,16,17] (mean value: 2022 Int.$8400/ha). Consequently, the assisted forest restoration project conducted in the cleared area (10.00 ha) as primary remediation was valued in 2022 Int.$ 84,000. The assisted forest restoration project conducted in the compensatory remediation area (8.05 ha) was valued in 2022 Int.$ 67,620.

The updated cost of land acquisition for compensatory remediation varied from 2022 Int.$1828 to 3769/ha[18] (mean value: 2022 Int.$ 2798/ha). Therefore, the acquisition of 8.05 ha for compensatory remediation was valued in 2022 Int.$ 22,523.

Accordingly, based on the mean values of timber, forest restoration projects and land acquisition, 10.00 ha of Amazon primary rainforest illegally cleared in 2023, with primary and compensatory remediations starting in 2023, was economic evaluated in 2022 Int.$ 341,611. Valuations based on the minimum and maximum values of timber, forest restoration projects and land acquisition are shown in Figure S6. Mean valuations considering discount rates varying from 1 % to 5 % are shown in Figure S7.

4. Discussion

A comparison of the results produced by the framework and the

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[10] As released by the Organization for Economic Co-operation and Development (OECD) at https://doi.org/10.1787/067eb6ec-en accessed on 11/08/2023.

[11] Purus National Forest Manangement Plan – 2009, available at https://www.gov.br/icmbio/pt-br/assuntos/biodiversidade/unidade-de-conservacao/unidades-de-biomas/amazonia/lista-de-ucs/flona-do-purus accessed in 25/07/2023.

[12] https://imazon.org.br/PDFimazon/Portugues/precos%20da%20madeira/Precos_10.pdf accessed in 25/07/2023.

[13] It might be difficult to access the timber log value in the field. To overcome this difficulty, these values can be inferred by commercial values of the log products (e.g., obtained in governmental acquisitions) and a transforming factor from whole logs to wood pieces (see [5]). Brazilian Federal Police has been working to standardize such calculations. As a comparison, timber values obtained by the mentioned methodology is 2022 Int.$ 209/m^3, 12 % higher than the timber mean value considered in this section.

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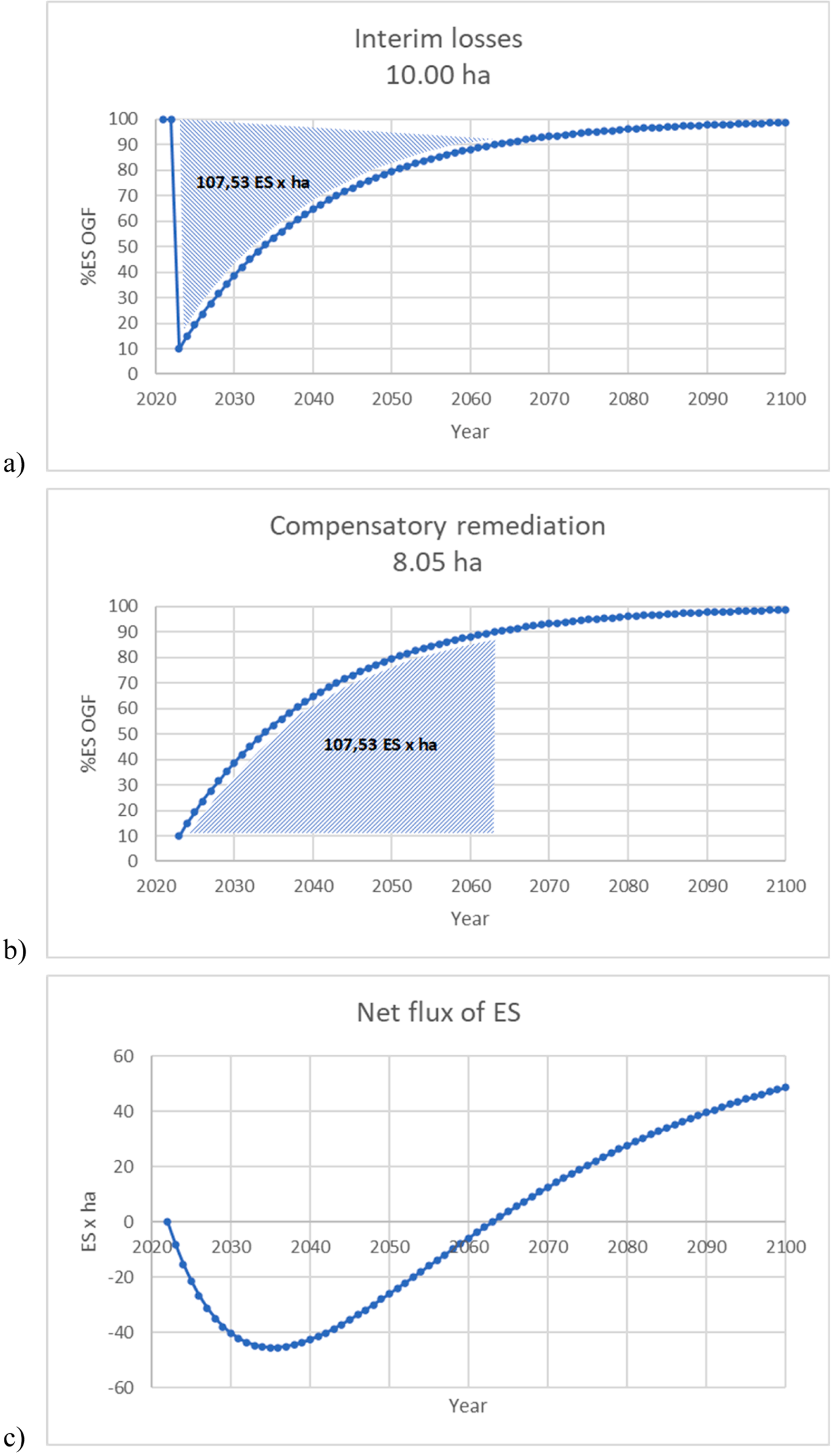

Fig. 2. a) Graphic illustration of interim losses caused by illegal clearing in 10.00 ha of Amazon primary rainforest. b) Graphic illustration of compensatory remediation in 8.05 ha. c) Net flux of ES (in ES x ha) until 2100, considering that deforestation of 10.00 ha occurred in 2023 and primary (10.00 ha) and compensatory (8.05 ha) remediations started in 2023.

average tropical forest value described in the literature was possible by using Eq. 3 described in Pavanelli & Voulvoulis [18]. Shortly, ES provision increases with the level of integrity, complexity and/or species richness of ecosystems (Díaz et al., 2006). Considering the mean value of primary forests [25] inflation-adjusted[19] to 2022 Int.$ 3652/ha/year representing the economic valuation of the ES provided by Amazon primary rainforests at the climax successional stage, that is, realizing their full ES potential, it is reasonable to consider that earlier successional stages of the tropical forest provide less ES than its maximum capacity, consequently adding less economic value to the forests in these stages. Thus, a recently cleared area (10 % baseline, or 10 % of the ES of the OGF) would be valued in 2022 Int.$ 365/ha/year, and the ES not delivered would value 2022 Int.$ 3287/ha/year; a tropical forest under restoration (baseline 60 %, or 60 % of the ES of the OGF) would be valued 2022 Int.$ 2191/ha/year and the ES not delivered would value 2022 Int.$ 1460/ha/year.

Annual non-delivered ES values during forest restoration are adjusted according to the baseline level and the PVM. The deforestation value, or the aggregation of annual values during the interim loss period according to Eq. 3, yields 2022 Int.$ 392,713 as shown in Table S4 and Figure S8.

$$\textit{Illegal clearing value} = \sum_{i=1}^{40} \textit{Amazon primary rainforest value} \times \textit{Cleared area} \times \left(1 - \frac{\textit{Baseline}_i}{100}\right) \times \textit{PVM}_i \quad (3)$$

where:

i = interim loss year, from year 1 to 40;

Amazon primary rainforest value = 2022 Int.$ 3652/ha/year;

Cleared area = 10.00 ha;

Baseline_i = baseline value at year i, from 10 % after clearing to 90 % after 40 years; and

PVM_i = present value multiplier at year i.

As detailed in Section 3.4, the framework assessed the illegal clearing of 10.00 ha of Amazon primary rainforest at 2022 Int.$ 341,611. Utilizing Eq. 3, the value required to reach this sum in 40 years is 2022 Int.$ 3175/ha/year, as depicted in Table S5. Table 2 demonstrates that the framework's valuation surpasses that based on timber and forest restoration by 35 %, approaching 86 % of the mean primary forest value outlined in Taye et al. [25].

The framework calculates a compensatory remediation area of 8.05 ha, considering clearings and remediations occurring in 2023. It represents the smallest compensatory remediation area necessary to offset the calculated interim losses. Any delay in implementing primary or compensatory remediation would escalate the interim losses, necessitating larger compensatory remediation areas to offset them. Therefore, the framework also evaluates land use after clearings, assessing recent and past clearings as well as compensatory remediations implemented now or in the future. Figure S9 presents the linear relationships between the compensatory remediation area, clearings occurring before the base year (2023), and the start of remediation processes. Table 3 illustrates the increments in the valuation of illegal clearings depending on the use of cleared areas. Table S6 demonstrates the calculation of the net fluxes of ES depending on land use, while Figure S10 illustrates these net fluxes.

Table 2

Economic valuation of 10.00 ha of Amazon primary rainforest illegal clearing.

Valuation approach	Deforestation value (2022 Int.$)
Timber + forest restoration	251,468
Based on mean literature value [25]	392,713
This framework	341,611

The framework's valuation of illegal clearings relies on the costs of timber, land acquisition, and assisted forest restoration projects, which may vary depending on the distance from communities. Thus, the valuation of illegal deforestation may be location-dependent.

The former Amazonian agropastoral frontier has resulted in cleared lands now integrated into the agropastoral economy. These areas are typically distant from primary rainforests, prone to nutrient depletion, and entail high acquisition costs. In contrast, recently cleared lands within today's Amazonian agropastoral frontier are situated near primary rainforest fragments, facilitating seed dispersal and harboring soils with viable forest seed banks. Due to their distance from infrastructure such as roads and grain storage, they have lower acquisition costs. Therefore, the framework assigns lower values to illegal clearings within today's Amazonian agropastoral frontier compared to those in the former frontier, which are farther from primary tropical forest areas. This valuation approach aligns with the expected valuation of regionally scarce goods, assigning greater value to tropical forest ES where they are less abundant.

The uses of cleared lands within today's Amazonian agropastoral frontier area are intertwined with real estate speculation. Structures such as roads, settlements, health services, and schools significantly increase the value of these lands, driving the advancement of the agropastoral frontier. The framework considers the utilization of deforested land, enhancing valuation for illegal clearings that occurred in the past or those undergoing speculative processes.

The framework is sensitive to changes in the compensation period, discount rate, and ES recovery curve, directly affecting interim loss calculations and the extension of the compensatory remediation area, thereby resulting in economic effects in the valuation of illegal clearings. Sensitivity responses are presented in Supplementary Information – Framework sensitivities.

Brander [3] outlines primary valuation methods and their typical applications, such as replacement cost, which estimates the cost of replacing an ES with a man-made service and restoration cost, which estimates the cost of restoring degraded ecosystems to ensure provision of ES. As discussed in Section 3, illegal clearings in primary rainforests render forest restoration insufficient for offsetting interim losses, even with full restoration efforts. The framework proposes compensatory remediation on former forest areas, currently used as pastures or croplands, to offset interim losses. Unlike the replacement cost valuation method, which focuses solely on man-made service substitution, the framework emphasizes the delivery of ES by forest restoration. By addressing not only the restoration of illegally cleared areas but also aiming for the full restoration of all ES not provided by these areas, the framework extends the scope of the restoration cost valuation method, targeting the restoration of interim losses.

The framework calculates the lowest economic valuation to compensate for interim losses resulting from a 10.00 ha illegal clearing of Amazon primary rainforest at 2022 Int.$ 3175/ha/year. This figure aligns closely with meta-analysis valuations reported by [25] (2022 Int.$ 3652/ha/year) and TEEB (2022 Int.$ 3334/ha/year – see Box 1). The framework, based on compensating for illegally suppressed ES, evaluates illegal clearings according to their location, utilization, and local market prices, providing defensible conservative estimates for policymakers regarding illegally cleared areas lacking economic valuation studies.

The framework calculates the restoration cost of ES, accounting for past losses and future gains. This cost, influenced by locational attributes, comprises land acquisition, reforestation projects, and timber values. However, it simplifies by assuming suppressed ES values are identical across all cleared areas. Expected conditions include:

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[19] https://www.bls.gov/data/inflation_calculator.htm accessed in 26/07/2023.

Table 3
Valuation of illegal clearings depending on the use of cleared areas.

Clearing occurred in	Remediation started in	Valuation (2022 Int.$)				
		Timber	Primary remediation	Compensatory remediation	Land acquisition	**Total**
2018	2023	167,468	84,000	98,532	32,820	**382,820**
2023	2023			67,620	22,523	**341,611**
2023	2026			94,668	31,533	**377,669**

- Illegal clearings suppressing above-average valued ES (e.g., spiritual areas), with compensation occurring in average-valued areas. As the framework intends to compensate ES in both quality and quantity, based on average quality, illegal clearings would be undervalued and considered the minimum deforestation value;
- Illegal clearings suppressing average-valued ES, with compensation occurring in special areas (e.g., ecological corridors, educational, cognitive or spiritual areas). Compensation ES values are expected to surpass suppressed ES values. Environmental policies can strategically leverage this framework feature when selecting locational alternatives.

The framework can be applied to other areas of illegal clearings, utilizing appropriate ES restoration curves based on forest classification. The forest restoration model described by Eq. 2 is applicable to Amazon primary rainforest. Forests falling outside this classification may exhibit different restoration curves, directly affecting interim loss calculation and, consequently, the cost of interim loss restoration through compensatory remediation. Furthermore, when applying the framework to non-primary forest areas (e.g., mid-stage regenerated secondary forests), it's important to consider that fully restoring the deforested area to old-growth secondary forest may yield sufficient ES to offset interim damage without necessitating compensatory remediation areas.

Illegal deforestation is considered a criminal act under Brazilian law and generally occurs in areas without previous forest valuation studies. The economic valuation of illegal deforestation is important in different aspects:

- Criminal: for criminal proceedings and civil reparations against those responsible for deforestation;
- Socioeducational: to inform society of the minimum value of environmental losses caused by deforestation;
- Economic: demonstrating that gains from forest conversion may be lower than the value of ES provided by the forest; and
- Environmental: for defining a minimum compensation cost for interim losses, which can be used in the definition of environmental policies at local, regional, and national levels.

In the absence of specific valuation studies of Amazon areas affected by illegal deforestation, average values of meta-analyses published in the literature may suggest the economic value of environmental damage. Critics argue that this approach cannot be confused with the benefit transfer method, noting a wide range of ES values in primary valuation studies and the lack of presentation of result uncertainties in many studies. To avoid such criticisms, many assessments of environmental damage consider only the value of timber and the restoration of the deforested area, a valuation acknowledged as an underestimate of the environmental damage.

Primary valuation studies may be time-consuming, expensive, and require expertise [14], demanding statistical analysis ranging from simple to very complex [26]. Thus, the application of any valuation method to real-world decision-making is conditioned by trade-offs between relevance (salience to the decision's context), robustness (reliability and representation), and resources (the time, financial, technical, and human resources required to design and apply valuation) [17].

The application of the framework in valuing Amazon illegal deforestation is not costly in terms of material, human, or temporal resources and provides a tangible minimum local value of the forest. It is based on ecological recovery and focuses on fully compensating for the same ES suppressed by deforestation. The economic values presented by the framework are based on local market values, respecting the economic model of supply and demand for products, services, and logistics. Furthermore, the framework can value land use after illegal deforestation, whether the deforestation occurred in the past or the recovery of the deforested area is to be carried out in the future.

The application of the framework demonstrated that the value of illegal deforestation in the Amazon reached the magnitude defined in the literature, without being subject to criticisms directed at its average values.

5. Conclusion

This work presents a framework for the economic valuation of Amazon primary rainforest clearings, considering the total amount of ecosystem services rather than individually evaluating the various ES suppressed. The framework's results contribute to the debate on points intrinsically related to illegal Amazon deforestation: the variation of forest value in different deforestation fronts; the evolution of forest value during the movement of the agropastoral frontier; the economic use given to the deforested land; and the cost–benefits of the activities carried out on it.

The application of the framework to 10 ha of illegally cleared Amazon primary rainforest resulted in an economic valuation of 2022 Int.$ 341,611, or 2022 Int.$ 3175 per hectare per year, 35 % higher than those based only on timber and cleared area restoration.

The framework demonstrates how the use of the cleared area can be translated into forest value: the longer the deforestation occurred in the past and the longer the delay in forest restoration, the larger the amount of ES not delivered to its surroundings, and the higher deforestation values produced by the framework. It puts into perspective activities carried out in deforested areas: their total economic gains must be compared to the total amount of ES that the cleared area ceased to provide from the date of deforestation until its complete restoration. This allows society to decide whether activities that generate limited local economic gains compensate for the loss of local ES provided by the tropical forests.

The framework is sensitive to the parameters of compensation period, discount rate, and ES recovery curve. These parameters affect interim losses calculation and the extension of the compensatory remediation area, resulting in economic effects on forest valuation. By describing the tangible economic value of Amazon primary rainforest clearings, the framework aims to enhance society's understanding of Amazon deforestation costs and benefits.

The framework's application may raise the perceived value of Amazon primary rainforest by society, stimulating payments for ecosystem services (PES) policies and discouraging predatory forest exploitation. The requirement for compensatory remediation areas calculated by the framework can alter the current forest exploitation pattern, serving as an additional law enforcement tool to assign responsibility for inhibiting illegal deforestation.

Disclaimer

The article expresses only the opinion of the authors and not the

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Code availability

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Declaration of Competing Interest

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.forsciint.2024.112307.

Data Availability

Data may be available upon request.

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