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Conflicts and opportunities for commercial tree plantation expansion and biodiversity restoration across Brazil

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Abstract

Substantial global restoration commitments are occurring alongside a rapid expansion in land-hungry tropical commodities, including to supply increasing demand for wood products. Future commercial tree plantations may deliver high timber yields, shrinking the footprint of production forestry, but there is an as-yet unquantified risk that plantations may expand into priority restoration areas, with marked environmental costs. Focusing on Brazil—a country of exceptional restoration importance and one of the largest tropical timber producers—we use random forest models and information on the economic, social, and spatial drivers of historic commercial tree plantation expansion to estimate and map the probability of future monoculture tree plantation expansion between 2020 and 2030. We then evaluate potential plantation-restoration conflicts and opportunities at national and biome-scales and under different future production and restoration pathways. Our simulations show that of 2.8 Mha of future plantation expansion (equivalent to plantation expansion 2010–2020), ~78,000 ha (3%) is forecast to occur in the top 1% of restoration priority areas for terrestrial vertebrates, with ~547,500 ha (20%) and ~1,300,000 ha (46%) in the top 10% and 30% of priority areas, respectively. Just ~459,000 ha (16%) of expansion is forecast within low-restoration areas (bottom 30% restoration priorities), and the first 1 Mha of plantation expansion is likely to have disproportionate impacts, with potential restoration-plantation overlap starkest in the Atlantic Forest but prominent in the Pampas and Cerrado as well. Our findings suggest that robust, coherent land-use policies must be deployed to ensure that significant trade-offs between restoration and production objectives are navigated, and that commodity expansion does not undermine the most tractable conservation gains under emerging global restoration agendas. They also highlight the potentially significant role an engaged forestry sector could play in improving biodiversity outcomes in restoration projects in Brazil, and presumably elsewhere.

1 | INTRODUCTION

Enormous, land-hungry global restoration commitments are occurring concurrently with swelling demand for tropical commodities. While such demand continues to be a key driver of tropical deforestation (Seymour & Harris, 2019), it is now also a growing potential competitor for priority lands for restoration (Edwards, Cerullo, et al., 2021). A major challenge is therefore how to deliver biodiversity benefits from restoration while also reconciling growing production needs, and therefore ensuring that restoration activities do not simply displace production elsewhere with overall net harms to biodiversity (Bateman & Balmford, 2023).

Tree plantations grown to provide wood products are a rapidly expanding component of tropical landscapes, growing by 32.2 million hectares (Mha) between 2000 and 2012 and occupying 131 Mha of lands worldwide in 2020 (FAO, 2020). New markets for construction and bioenergy (Mishra et al., 2022; Peng et al., 2023) and the inability of natural production forests to support growing timber demand (Piponiot et al., 2019; Shearman et al., 2012; Sist et al., 2021) are forecasted to promote substantial additional tropical plantation expansion in the near future (Edwards, Cerullo, et al., 2021; Lewis et al., 2019; Peng et al., 2023). Meanwhile, ambitious restoration commitments, including under the UN Decade on Ecosystem Restoration and the Bonn Challenge to restore 350 Mha of degraded lands by 2030, may also drive substantial plantation cover increases if these are counted towards national restoration targets (Lewis et al., 2019). Understanding the magnitude, severity, and extent of possible conflicts between plantations and ecosystem-focussed restoration priorities at large spatial scales is therefore critical for developing coherent land-use plans that deliver wood production while maximising carbon and biodiversity restoration gains, and reducing environmental trade-offs. Such understanding is also important in the context of identifying stakeholders, private actors and commodity production models with particular scope for influencing restoration outcomes, either positively or negatively (Brancalion et al., 2020; Löfqvist et al., 2023).

Tree plantations typically hold limited conservation value compared to native forests, harbouring lower species abundance, aboveground biomass, water provisioning, and soil erosion control than naturally regenerating forests globally (Hua et al., 2022). Nevertheless, the substantially higher yields generated within tree plantations means that they may deliver significant environmental benefits if they spare natural forests from wood harvesting, or reduce harvest intensity within ecosystems earmarked for production (Betts et al., 2021; Cerullo, Barlow et al., 2023, Cerullo, França et al., 2023; Harris & Betts, 2023). Although evidence of such passive sparing effects is inconclusive (Pirard et al., 2016; Warman & Nelson, 2016), plantations clearly have a critical role in fulfilling timber production needs at least cost to native habitats (Harris & Betts, 2023), particularly in light of a 54% predicted increase in wood demand between 2010 and 2050 (Peng et al., 2023). This has spurred the design of alternative tree plantation models which attempt to increase resilience against climate change and maximise environmental and conservation benefits (Brancalion et al., 2020; Messier et al., 2021), including by targeting plantations to replace agropastoral land uses, especially degraded pastures.

Crucially, the socio-environmental impacts of tree plantations can be very different depending on where they are established (Edwards, Cerullo, et al., 2021; Fagan et al., 2021; Veldman et al., 2015). Where plantations replace native ecosystems or occupy non-forest biomes, they can reduce biodiversity and ecosystem services considerably (Barlow et al., 2007; Bond et al., 2019; Edwards, Cerullo, et al., 2021; Hua et al., 2022), and drive synergistic social harms through land rights and access conflicts (Erbaugh et al., 2020). Plantation establishment within grasslands or drylands reduces hydrological functioning (Schwärzel et al., 2020), increases flammability and the risk of invasion by commercial species into native habitats (Matos et al., 2022), and undermines open-habitat and forest specialist biodiversity, including in protected areas and their environs (Bond et al., 2019; Costa et al., 2022; Fagan et al., 2021). Moreover, where plantations compete with the most valuable areas where restoring native habitats would deliver disproportionate benefits, the opportunity costs for carbon and biodiversity are expected to be stark (Hayek et al., 2021). A key question is therefore where future plantation expansion is likely to occur and to what extent this will impact the opportunity for ecosystem-focussed restoration.

We investigate these key issues in Brazil, one of the largest timber producers in the tropics, the world's most biodiverse country, and a nation that has committed to 12 Mha of restoration under Nationally Determined Contributions (NDCs) and the Bonn Challenge. We recognise the critical importance of quantifying the impacts of tree plantation expansion on key socio-ecological considerations, including water security and land tenure (Bispo et al., 2023; Rakotonarivo et al., 2023), but focus here on conflicts and opportunities for aligning plantation production with the enhancement of biodiversity. This emphasis is rooted in the growing prevalence of biodiversity improvement goals under evolving restoration initiatives (Edwards, Cerullo, et al., 2021; Edwards, Massam, et al., 2021), and on clearly evidenced disparities in biodiversity between native restoration and plantation programmes (Hua et al., 2022). As tree monocultures represent nearly half of the restoration area pledged by countries in the Bonn Challenge (Lewis et al., 2019), optimising the balance between plantations and biodiversity restoration is critical.

Specifically, we address three objectives to: (1) map predicted future tree plantation expansion across Brazil between 2020 and 2030; (2) quantify potential conflicts and opportunities for pursuing

tree plantation expansion and high-value ecosystem restoration in tandem at national and biome scales; and (3) simulate different plantation expansion pathways to determine how conflicts and opportunities vary according to the land area devoted to plantation expansion or ecosystem restoration. Our results can help to inform how the critical goals of increased timber production and native habitat restoration might be navigated successfully at national scales.

2 | METHODS

2.1 | Predicting future monoculture tree plantation expansion across Brazil between 2020 and 2030

Using geospatial data on the distribution of land-uses, and socio-economic and biophysical variables, we fitted random forest models to predict plantation expansion likelihood for 2020–2030. Random forest is an ensemble method that can be used for classification, and which creates multiple decision trees based on subsampling predictors in a training dataset to maximise predictive accuracy of a class (e.g., a 0 or 1 outcome). The fraction of independent trees assigned to a given class in a cell can be scaled and treated as a measure of the probability of class presence (Dunnett et al., 2022; Simon et al., 2023). Our predictive modelling approach consisted of four steps (Figure 1). First, we trained random forest models to predict the probability of plantation expansion between 2000 and 2010, using predictor variables from 1995 to 2000 and information on expansion dynamics up to 2010 to stratify training points (*Training Models 2000–2010*; Figure 1a). Second, we applied these models to predict the 2010–2020 plantation expansion, using equivalent predictors (i.e., from 2005 to 2010; *Testing Models 2010–2020*; Figure 1b). Third, we evaluated how accurate our models were in predicting true plantation expansion for 2010–2020, using multiple evaluation metrics, and comparing model performance to logistic regression models that considered only spatial contagion predictors (*Evaluating Models 2010–2020*; Figure 1c). Fourth, we applied the model built using 2000–2010 data that best predicted what happened 2010–2020 to generate a plantation expansion probability surface for between 2020 and 2030 across Brazil (*Predicting 2020–2030 expansion probability*; Figure 1d).

2.2 | Training RF models 2000–2010

2.2.1 | Response and predictor variables

We trained our models to predict a binary response depicting whether 10 km^2 cells experienced plantation expansion between 2000 and 2010 (1—expansion, 0—no-expansion). For 2000 and 2010, we obtained annual 30 m resolution monoculture tree plantation distributions ('Class 3.3, Silvicultura/Forest Plantation') from the MapBiomas database (MapBiomas Version 7, 2022), which maps Brazil's land use cover and change through time. Monoculture tree plantations (hereafter plantations) described coverage of tree species

planted for commercial purposes. In Brazil, they mostly consist of eucalypts and pine tree, with 75.8% and 19.4% of the planted area, respectively (Indústria brasileira de árvores, 2022). We determined proportional plantation cover for every 10 km^2 cell across Brazil, and used a threshold of >5% plantation expansion over 10 years to categorise cells as experiencing plantation expansion or no expansion. This threshold is greater than the reported commission error in the MapBiomas product accuracy assessment for classification of tree plantations, which is based on specialists classifying 30 m Landsat images annually between 1985 and 2021. We tested different binary thresholds of plantation expansion (10% and 15%, respectively), to see how sensitive our models were to more conservative expansion thresholds.

For predictors of expansion, we used spatially explicit information from both within 10 km^2 cells (land-use cover, population size, accessibility to market, biophysical suitability, opportunity costs), from 50 and 100 km^2 buffers around cells (plantation cover and change), as well as municipality-level predictors (average municipality farm size and biophysical suitability). All predictors (Table S1) were reprojected and, in some cases, aggregated, to 10 km^2 in Mollweide projection. To remove variables explaining the same variation we removed predictors >0.7 Pearson's correlation from the sample of training points, retaining the most recent predictor to the year 2000 (Figure S1).

2.2.2 | Training point stratification

Between 2000 and 2010, less than 1.5% of 10 km^2 cells underwent >5% plantation expansion. Due to this scarcity, if we randomly selected training points from across Brazil, we would insufficiently sample plantation-expansion cells. Previous research demonstrates that such under-representation can bias probabilistic predictions of rare events (Cushman et al., 2017). Therefore, to build our model training sample we selected all expansion cells and then used random stratified sampling to provide a disproportionately high fraction of expansion cells, testing whether this influenced model performance. In the first instance, our training sample comprised a 1:1 ratio of expansion versus no-expansion points, as suggested for predicting rare outcomes from zero-inflated, imbalanced class ratios (Barbet-Massin et al., 2012). We also tested the effects of providing 2, 4, 8, or 16 times the number of non-expansion points, refitting random forest and logistic regression models for each training sample ratio.

2.2.3 | Random forest model

All random forest models were run in Google Earth Engine using default tuning parameters and 500 trees. Models with different fractions of expansion cells, and with different threshold definitions of plantation expansion thus generated a range of random forest structures, based on different subsampling of the full set of predictor variables. Each model therefore explored which combinations
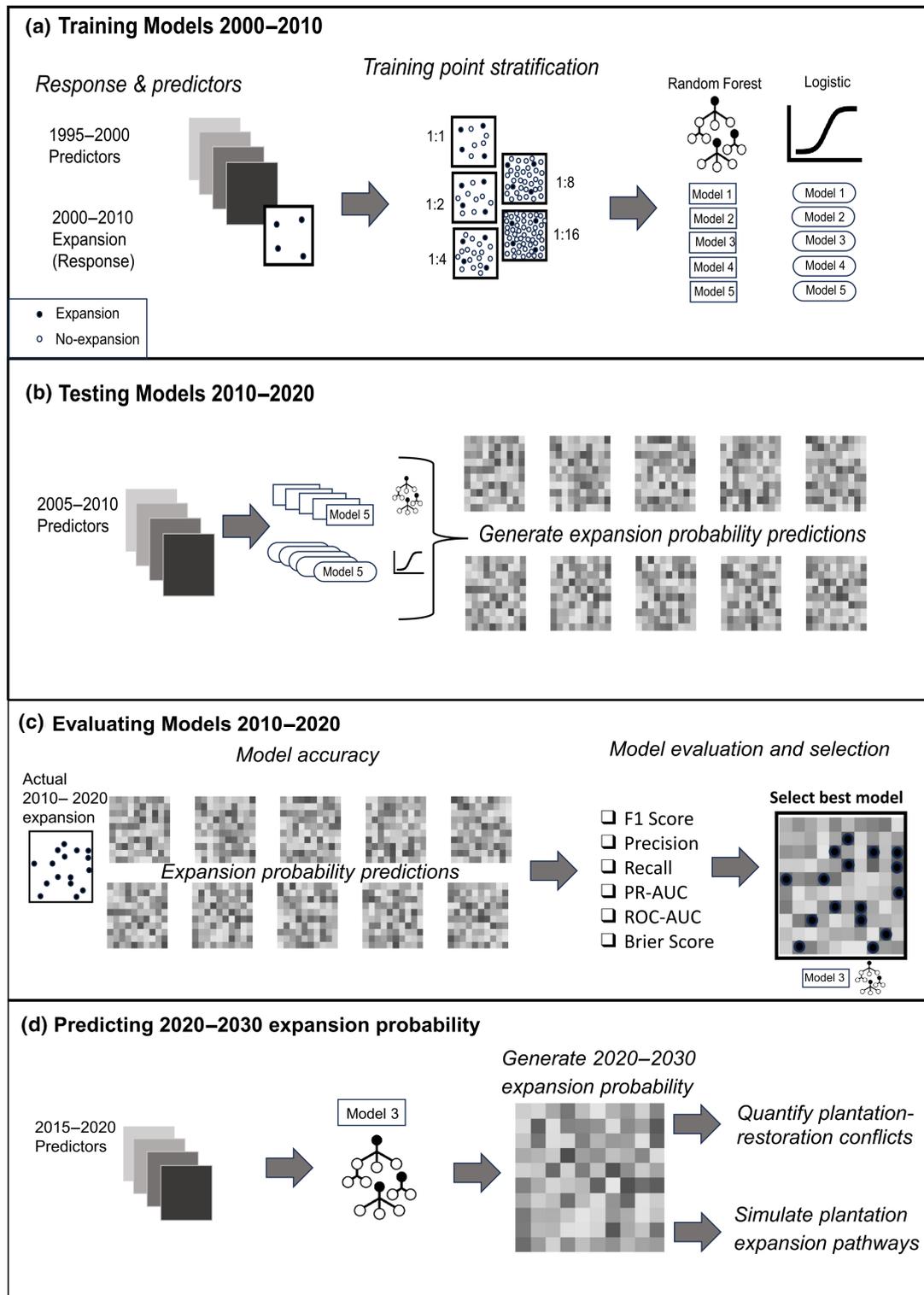
FIGURE 1 Overview of methodolgical approach. Logistic and random forest models were trained to predict tree plantation expansion 2000–2010, based on biophysical, economic and social predictors from 1995–2000, and with training points randomly stratified to include varying proportions of no-expansion to expansion cells (a). These models were then tested by using the same model structures to generate plantation expansion probability surfaces for 2010–2020, based on predictors from 2005–2010 (b). Models were evaluated against actual 2010–2020 expansion using a suite of evaluation metrics to select the best-fitting model (c). This best model was then used to generate a plantation expansion probabilitiy surface 2020–2030, based on 2015–2020 predictors, which was then used for subsequent quanitification of plantation-restoration conflicts and simulation of different expansion pathways (d). Note that we repeated these steps using more-conservative thresholds for defining binary plantation expansion (10% and 15% expansion thresholds).

of variables maximised predictive accuracy for a given cell, whereas comparisons between models provide an evaluation of the effect of providing different expansion thresholds or proportions of training points.

2.3 | Testing RF models 2010–2020

Having produced a set of random forest models for between 2000 and 2010, we applied these to generate expansion predictions for between 2010 and 2020 using predictor variables for the focal year of 2010. Having computed predictions for between 2010 and 2020 using different model structures, we tested their predictive performance in R (version 4.2.2). We interrogated the key drivers of plantation expansion by calculating Variable Importance for our best-fitting model as a measure of the predictive power of model variables (Simon et al., 2023). Since random forests use decision trees to identify non-linear, context-dependent interactions between predictor variables, it is not straightforward to determine the directional effects of different predictors, as these can vary for different cells. For visualisation purposes, we provide plots showing how predicted plantation expansion probability is related to each model covariate (Figure S2).

2.4 | Evaluating RF models 2010–2020

2.4.1 | Model accuracy

An assessment of a predictive model should closely match the intended model use case. As we were principally interested in predicting future tree plantation expansion in 2020–2030, we assessed how well models trained on 2000–2010 data could predict the subsequent decade of plantation expansion (2010–2020). By selecting the best-fitting model predicting 2010–2020 expansion, we reduced overfitting our models to the training period (2000–2010). We used six complimentary performance metrics to evaluate model performance: three threshold-independent metrics (Brier Score, AUC-ROC, AUC-PRC), which evaluate the continuous pattern of probabilities in predicting binary outcomes; and three threshold-specific measures (Precision, Recall, F1 Score), which required converting continuous predictions into Boolean expansion or no-expansion outcomes, to enable a cross-tabulation based evaluation. To generate Boolean outcomes, we drew a Bernoulli sample from our continuous surface and assigned cells as undergoing expansion, or not (Sofaer et al., 2019). Table S2 describes each evaluation metric and how they were calculated.

2.4.2 | Model evaluation and selection

We compared RF model performance to naïve logistic regression models. Since the factors driving plantation expansion are not random, it would not be appropriate to compare model performance to random allocation (Rosa et al., 2014). We thus included all spatial contagion predictors into our naïve logistic model (plantation cover within 50 and 100 km^2 buffers, and plantation cover change in both buffers between 2007–2010 and 2000–2010), as this allows us to model the value added by incorporating economic, biophysical, and social drivers in our models. As with RF models, we tested the consequences of changing the proportion of expansion and non-expansion cells in the training sample, and of varying the plantation expansion threshold.

2.5 | Predicting 2020–2030 expansion probability

Using our suite of evaluation metrics we selected the best-fitting model for predicting 2010–2020 plantation expansion, and then applied this best-performing model to the 2020–2030 covariate layers. This model-derived probability surface for tree plantation expansion was then used to quantify plantation-restoration conflict and opportunities, and as a basis for simulating different expansion pathways.

2.6 | Quantifying plantation-restoration conflicts and opportunities at national and biome scales

2.6.1 | Restoration priority

We quantified plantation-restoration conflicts and opportunities by intersecting expansion probability and restoration priorities at national and biome scales. Our measure of restoration priorities was from Strassburg et al. (2020), who estimated the avoided extinctions per hectare associated with returning pasture or agricultural land to original habitat cover. This used IUCN species distribution maps, elevational ranges, and habitat preference information to determine the spatial distribution of the area of suitable habitat for 5012 mammals, 6515 amphibians, and 11,121 bird species globally, and then (following Duran et al., 2020) used a species-area function to determine species-level reductions in extinction risk from restoring suitable habitat. To rank the global significance of restoration in different areas of Brazil, we resampled avoided extinctions per hectare across species to 10 km^2 by computing the sum of input pixels, and rescaled values between 0 and 1, relative to the highest value observed in Brazil.

2.6.2 | Bivariate comparison

To visualise the relationship between our plantation expansion probability layers and restoration priority rankings, we created a bivariate grid for Brazil. We reclassified input layers (both bounded between 0 and 1) into 10 bins of equal representation, and then combined our plantation expansion layer with restoration priority areas to give

100 unique values across Brazil showing country-level conflict patterns. However, because Brazil has a number of biome-specific restoration initiatives (e.g., Crouzeilles et al., 2019) that are also linked with compliance to the Native Vegetation Protection Law, it is also important to understand how future plantation expansion probability overlaps with biome-specific restoration priority areas. Hence to further visualise the relationship within each Brazilian biome, we rescaled ecosystem restoration priorities for each biome and built biome-level bivariate analyses.

2.7 | Simulating different plantation expansion pathways

Last, we used our plantation expansion probability layer to simulate different pathways under different restoration and plantation expansion. For a given static threshold of restoration priority areas (top 1%, 10%, or 30% of restoration areas), we simulated future plantation expansion based on our chosen model, iteratively adding plantation cover into the highest-ranking $10\,km^2$ cell, then the next highest, and so on, until we reached 4Mha of expansion, which is approximately equivalent to a 50% increase in current tree plantation cover. We allocated 12% cell-level expansion per cell as this corresponds closely to the mean area of decadal plantation expansion that occurred within plantation cells undergoing expansion between 2000–2010 and 2010–2020 (11% and 12%, respectively). To incorporate uncertainty into the spatial ordering of future tree plantation expansion and thus amount of overlap with restoration priority areas, we simulated 1000 bootstraps of plantation expansion. For each bootstrap, instead of allocating expansion in descending order of probability, we randomly added plantation cover to cells with a plantation probability >0.1 (giving a total candidate pool of 5,602,440ha of potential area that plantations could expand into), beginning each bootstrap with a different random seed. We also report on the area of expansion forecast in low-restoration value areas, defined as restorable cells falling within the bottom 30% of restoration priority areas.

3 | RESULTS

3.1 | Model performance and selection

The random forest models outperformed logistic models at predicting tree plantation expansion between 2010 and 2020 for all evaluation metrics, with higher AUC-ROC and lower Brier Scores, and with models predicting expansion thresholds of >5% performing best (Figure S3). AUC-ROC alone can give a misleading representation of model performance in cases of high class imbalance, such as ours, as AUC-ROC considers true negatives, and thus incorporates correct predictions of absence (Sofaer et al., 2019). In comparison AUC-PRC, which does not consider true negatives, showed lower model performance, with the highest AUC-PRC (0.37) when predicting

>5% expansion thresholds, and with a 1:1 ratio of expansion and no-expansion cells in the training sample. This was driven by models predicting tree plantation expansion having high recall (~75%, meaning that 75% of expansion occurred in areas predicted to be of high probability), but lower precision (between 10% and 35% for >5% expansion threshold, meaning that only 10%–35% of areas predicted to have a high probability of expansion actually underwent expansion). Overall, this means that our models are likely to overestimate plantation expansion probability. While it is difficult to correctly identify which exact cells will undergo expansion over the subsequent 10years (low precision), the domain within which plantation expansion occurs can be predictably identified (high recall), allowing a robust investigation of how this expansion domain intersects with priority restoration areas.

We selected as our best-performing model a >5% expansion threshold with 1:4 ratio of expansion to no-expansion cells in the training sample; as this gave the best balance between maximising both F1 (the harmonic mean of precision and recall) and AUC-PRC. For this model, we assessed the relative importance of predictors in driving plantation expansion for our test period of 2010–2020 by comparing Variable Importance (Figure S4). Within-cell values of slope, population size, proximity to market and biophysical suitability were the most important predictors of tree plantation expansion. The average size of farms in a municipality and the change in plantation cover in a 100km buffer around the cell were strong outside-cell predictors of long-term expansion dynamics, followed by biophysical suitability at municipality scales in 2010.

3.2 | Future plantation expansion

Expansion hotspots are distributed chiefly in the Atlantic Forest biome, especially in southern Bahia, northern Espirito Santo, northeastern Paraná, and central Santa Catarina. Additionally, hotspots are located in the southern Cerrado of central Minas Gerais and eastern Mato Gross do Sul. Within the Pampas and Caatinga biomes, high expansion probability is mostly concentrated in northeast and southeast Rio Grande Do Sul, and eastern Bahia, respectively (Figure 2; Figure S5). Emerging expansion hotspots in the Amazon biome are clustered in western Maranhão, northern and southwestern Pará, south-eastern Amapá, eastern Roraima, and across a diffuse area of Mato Grosso.

3.3 | Overlap with restoration priority areas

Areas with the highest values for both plantation expansion and restoration priorities (purple colours, Figure 3) show where plantation expansion may carry the largest forgone restoration benefits. These are located principally in the Atlantic Forest biome and to a lesser extent in the southern Cerrado and eastern Pampas (Figure 3). When we rescaled restoration priorities at a biome scale to account for biome-focused restoration commitments (Figure 4), we found plantation
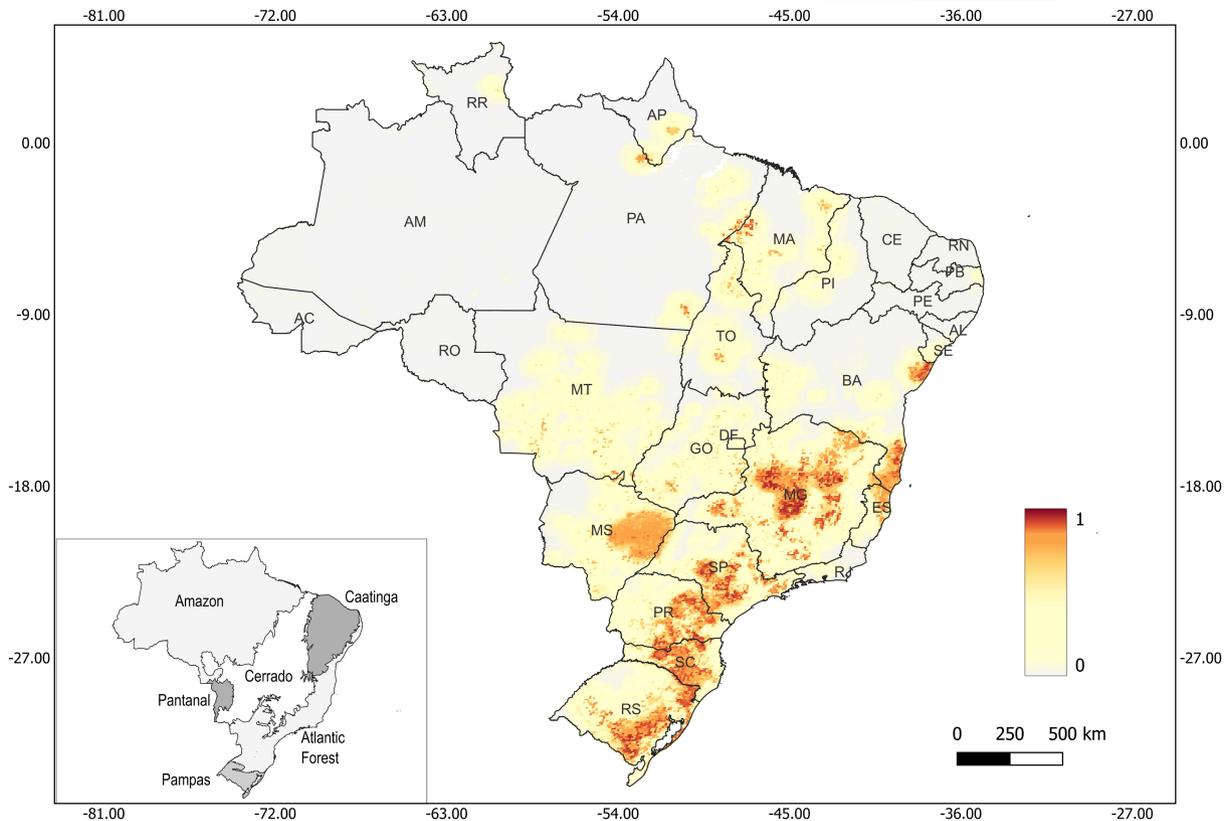
FIGURE 2 Probability of tree plantation expansion between 2020 and 2030. Probability of plantation expansion, bounded between 0 (low) and 1 (high), represents the output of a random forest classification model. This model was trained to predict 2000–2010 plantation expansion, with model accuracy tested as the ability to predict 2010–2020 expansion outcomes. The model shown above predicts the likelihood of 10 km^2 cells across Brazil undergoing a >5% expansion in plantation cover between 2020 and 2030, based on a combination of biophysical, socio-economic and land-used based predictors. Outlines and initials denote Brazilian states. See Figure S5 for the effects of choosing different expansion thresholds. Inset shows biome locations. State acronyms: Acre-AC; Alagoas-AL; Amapá-AP; Amazonas-AM; Bahia-BA; Ceará-CE; Distrito Federal-DF; Espírito Santo-ES; Goiás-GO; Maranhão-MA; Mato Grosso-MT; Mato Grosso do Sul-MS; Minas Gerais-MG; Pará-PA; Paraíba-PB; Paraná-PR; Pernambuco-PE; Piauí-PI; Rio de Janeiro-RJ; Rio Grande do Norte-RN; Rio Grande do Sul-RS; Rondônia-RO; Roraima-RR; Santa Catarina-SC; São Paulo-SP; Sergipe-SE; Tocantins-TO.

FIGURE 3 Probability of tree plantation expansion relative to restoration priority areas across Brazil. Probability of tree plantation expansion represents the output of a random forest classification model predicting the likelihood of 10 km^2 cells across Brazil undergoing a >5% plantation expansion 2020–2030 (see Figure 2). Areas of ecosystem restoration priority are from a previous study (Strassburg et al., 2020) that used species ranges and habitat preferences of terrestrial vertebrates (birds, mammals and amphibians) to determine the biodiversity value of restoring agricultural and pasture lands to native habitat. Outlines denote Brazilian biomes.
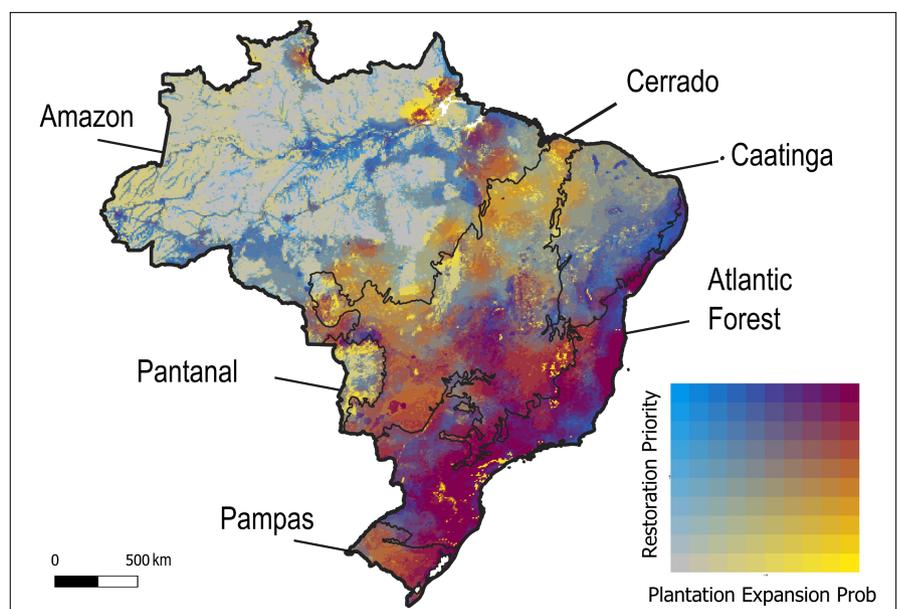
expansion and restoration conflicts in the Atlantic Forest are greatest in southern and eastern Bahia and northern Espirito Santo, and to a lesser extent in eastern São Paulo and Santa Catarina. For the Cerrado, the greatest conflicts are concentrated in central São Paulo and central Minas Gerais. For the Pampas, the Atlantic coast and northeast of Rio Grande Do Sul show the greatest conflict, whereas for the Pantanal, southwestern Mato Grosso and the eastern fringes of the biome in Mato Grosso Do Sul show the highest overlap. In the Caatinga, high-restoration priority areas and tree plantation expansion probability are largely focused in the southwestern limits of this biome, whereas they are focused in the north-eastern limits of the Amazon, south-eastern Amapá, and north-eastern Roraima. Areas with the highest values for plantation expansion and lowest restoration priorities (yellow colours, Figures 3 and 4) show where plantation expansion could proceed while incurring low biodiversity opportunity costs. This includes southern parts of the Atlantic Forest, central-northwestern parts of the Pampas, northwestern Caatinga, and in the northern and the western fringes of the Cerrado (Figure 4).

For all thresholds of high restoration priority areas, a disproportionate amount of tree plantation expansion is predicted within priority restoration areas (Figure 5; Figure S6). This is because of all restorable lands in Brazil, those with the highest biodiversity restoration value are more likely to undergo plantation expansion than the average for potentially restorable areas, with the top 10% of restoration priority areas showing the highest mean probability of plantation expansion (Figure S7). If 2.8 Mha of tree plantation estate is added by 2020–2030 (equivalent to expansion in Brazil 2010–2020), we predict that ~20% (547,440 ha) of this would occur within the top 10% of Brazilian restoration areas, with ~3% (78,120 ha) in the top 1% of restoration areas and ~46% (1,299,840 ha) in the top 30%. By comparison, ~459,000 ha (16%) of expansion is forecast within low-restoration areas (those with the lowest 30% restoration priority).

Of particular concern is the order of plantation expansion, with our models suggesting that plantation-restoration conflicts appear to be front-loaded and declining in percentage over time (Figure S6). Thus, the first 1 Mha of plantation expansion is predicted to intersect with ~4% (44,160 ha), ~30% (299,040), and ~61% (618,480) of the top 1%, 10%, and 30% priority restoration areas, whereas plantation expansion between 2 and 3 Mha would intersect with ~2%
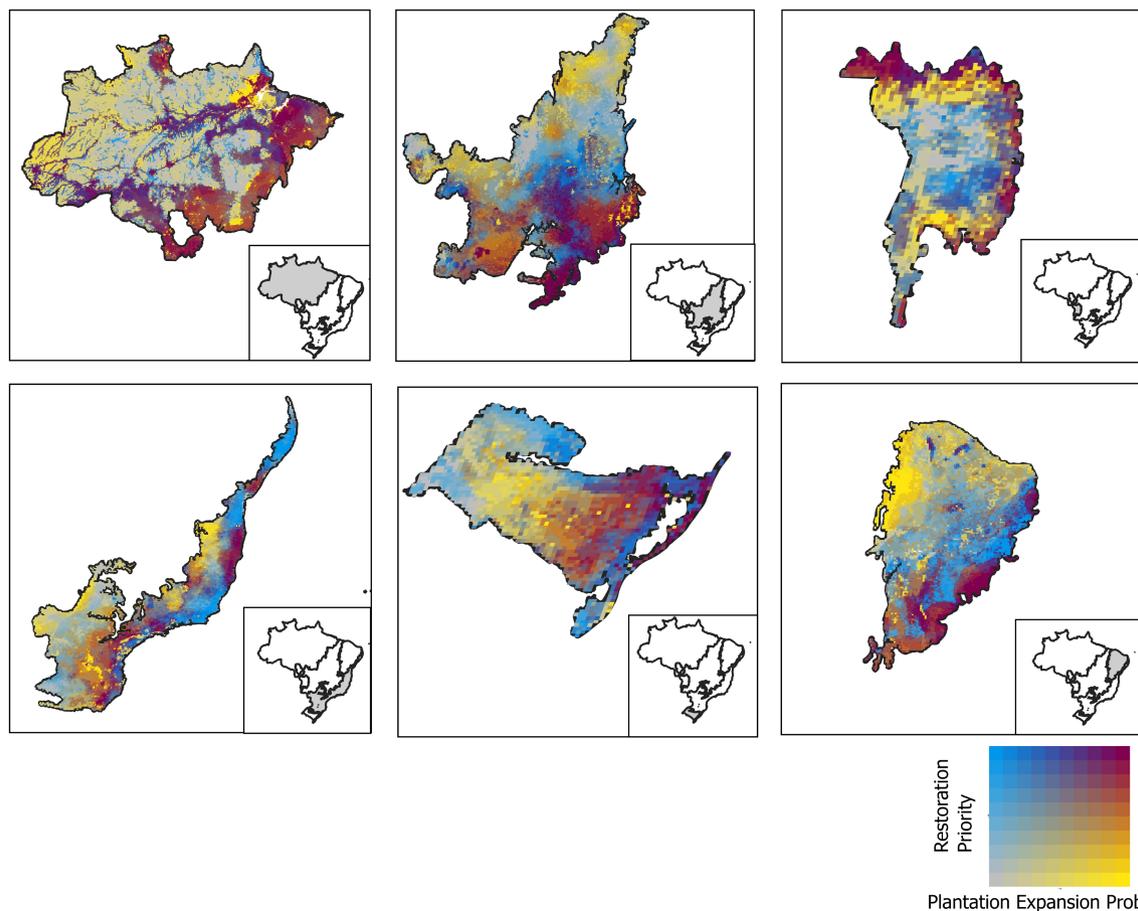

FIGURE 4 Probability of tree plantation expansion versus restoration priority area rankings, rescaled for the six Brazilian biomes: (a) Amazon, (b) Cerrado, (c) Pantanal, (d) Atlantic Forest, (e) Pampas, and (f) Caatinga. Areas of ecosystem restoration priority are from a previous study (Strassburg et al., 2020) and were rescaled between 0 and 1 for each Brazilian biome separately, to show the most valuable areas for restoring biodiversity on a per biome basis. Probability of plantation expansion is as described in Figure 2, and was not rescaled on a biome-basis.
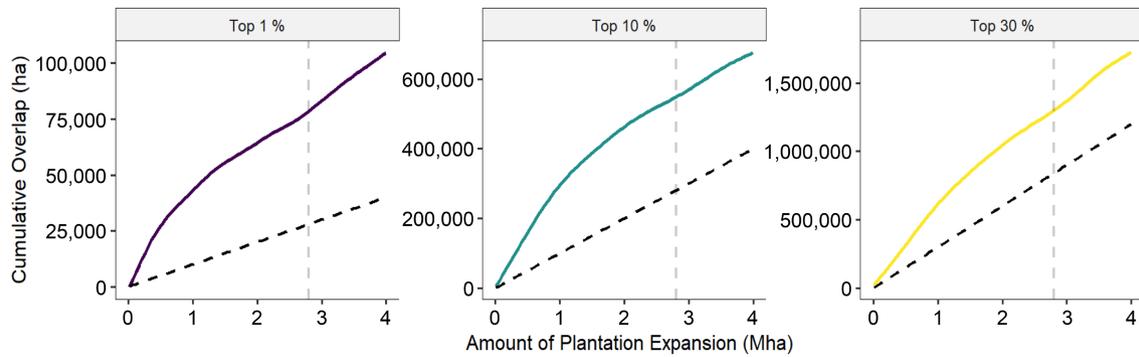
FIGURE 5 Overlap between restoration priority areas and tree plantation expansion in Brazil. We simulated future plantation expansion according to our random forest expansion probability layer, iteratively adding 12% plantation cover into the highest-ranking cells until we reached 4 Mha of tree plantation expansion. From left to right the coloured lines show the cumulative overlap of plantation expansion with areas in the top 1%, 10% and 30% for restoration of terrestrial vertebrates. The dashed grey line corresponds to ~2.8 Mha, equivalent to the amount of tree plantation expansion between 2010 and 2020. The dashed black line represents a scenario of proportional overlap, where plantation expansion overlaps with restoration priority areas in direct proportion to the area of land devoted to each. Where the coloured line falls above the dashed black line it suggests that restoration priorities occur disproportionately in areas that are likely to undergo plantation expansion. Note different *y*-axis scales.

(18,360), ~10% (104,400) and ~32% (319,200), respectively. A sensitivity check of the robustness of our findings, where we allocated tree plantation expansion stochastically rather than in descending order over non-zero values of our plantation expansion surface, maintained our finding of disproportionate overlap between expansion and restoration priority areas (Figure S8).

4 | DISCUSSION

Global restoration commitments are occurring alongside rapid expansion of tropical commodities, including for wood products (Fagan et al., 2021; Heilmayr et al., 2020; Hua et al., 2018). Future plantation expansion targeted to low-biodiversity areas may spare native habitats from environmentally damaging harvests (Hua et al., 2022; Warman & Nelson, 2016), helping fund large-scale native ecosystem regeneration (Brancalion et al., 2020). However, plantation expansion in restoration priority lands risks sacrificing biodiversity co-benefits and incurring severe environmental costs (Edwards, Massam, et al., 2021; Matos et al., 2020), unless active mechanisms are in place to couple production with the restoration of native habitats (Brancalion et al., 2020; dos Santos et al., 2020). We show that of 2.8 Mha of potential plantation expansion in Brazil (equivalent to 2010–2020 expansion), ~78,000 ha (3%) is predicted within the top 1% of terrestrial vertebrate restoration priority areas, versus 548,000 ha (20%) and 1,300,000 ha (46%) in the top 10% and 30% of priority areas, respectively, and with just 459,000 (16%) occurring the least valuable (bottom 30%) restoration areas. Moreover, plantation expansion probability and priority restoration areas co-occur such that the first 1 Mha of plantation expansion looks likely to have disproportionate impacts on the scope for restoring native biodiversity. Without active, multi-sectoral land-use planning, future plantation expansion may undermine effective delivery of conservation goals under restoration agendas.

Making predictions of rare events is challenging and our findings have three core limitations. Firstly, our model assumes historic drivers from 2010 to 2020 are appropriate for predicting plantation expansion 2020–2030; we do not consider how climate change, new plantation varieties, polices, roads or processing mills would alter plantation productivity and expansion dynamics (Florêncio et al., 2022; Nolte et al., 2013). Second, our model showed limited ability to identify precise expansion locations, chiefly because we infer decade-long plantation dynamics, which inherently have large uncertainty. Nevertheless, our models showed high performance in defining the probable expansion space 10-years in advance, and predictions of disproportionate plantation expansion in restoration priority areas were robust to sensitivity tests that generated expansion stochastically. Lastly, we use potential avoided extinctions for terrestrial vertebrates to identify restoration priorities, as we were principally interested in how much forecasted plantation expansion might either hamper effective conservation gains from restoration (Strassburg et al., 2020), or require the deployment of landscape production-restoration models that balance enhanced wood production and biodiversity (Brancalion et al., 2020; Hua et al., 2016). Incorporating additional taxa, social considerations, ecosystem services, or information on the feasibility of restoration—including data on natural regeneration potential or land costs—could generate different insights regarding where plantation-restoration conflicts may occur or could be mitigated (Brancalion et al., 2019; Crouzeilles et al., 2020).

4.1 | Identifying plantation-restoration conflicts and opportunities

Our findings show where near-term future plantation expansion is most likely, and also that the potential for plantation-restoration conflicts is most acute in the Atlantic Forest biome, a global hotspot

of small-ranged, endemic biodiversity (Brancalion et al., 2019) and a timber-production powerhouse. Historically, most Atlantic forest plantation expansion has occurred over cattle pastures, with 16% leading to deforestation (though this probably underestimates deforestation from displacing cattle into native habitats; Rosa et al., 2021). Previous studies have shown marked variation in the costs, biodiversity benefits, and feasibility for natural regeneration on degraded lands in the Atlantic Forest (Crouzeilles et al., 2020; Strassburg et al., 2019). Our analyses provide additional context by showing which lands coincide with high plantation expansion probability, and thus where restoration risks being ephemeral (Piffer et al., 2022; Rosa et al., 2021), or potentially fragmented within plantation-dominated landscapes, undermining conservation outcomes (Costa et al., 2022).

It is very important to note that in some places, plantation expansion in restoration priority areas may in fact be associated with improved biodiversity restoration outcomes on net—conflicts are not inevitable. Improved biodiversity outcomes in plantation expansion hotspots may occur if private plantation managers increase restoration financing (Löfqvist et al., 2023), or enhance landscape-level environmental compliance relative to business-as-usual management (d'Albertas et al., 2023). For example, Brazil is the largest global exporter of pulp, with nearly 70% of national production exported to foreign markets, resulting in nearly three quarters of plantation area in Brazil being certified (Indústria brasileira de árvores, 2022). A fundamental demand for obtaining plantation certification is compliance with the 2012 Native Vegetation Protection Law, which mandates restoration in Areas of Permanent Protection (around riparian buffers and on steep slopes) and Legal Reserves (a percentage of the landholding area that must be covered by native vegetation; Brancalion et al., 2016). Thus, where tree plantation expansion signals a change in management or land-ownership from cattle ranchers with predominantly low compliance to environmental regulations, towards managers of FSC-certified forestry plantations, this may help to promote the persistence or regrowth of restored habitats (Piffer et al., 2022), including as part of adherence to the Native Vegetation Protection Law (Soterroni et al., 2018). It is noteworthy that the forestry sector currently maintains as native vegetation 4.0 and 1.6 Mha of Areas of Permanent Protection and Legal Reserves, respectively (Soares-Filho et al., 2014).

Nevertheless, given recent findings that current private restoration investment already skews outcomes towards plantation-focussed or active-planting restoration models of typically lower biodiversity value, especially within areas deemed to have higher returns-on-investment from commodity production (Löfqvist et al., 2023), our findings warn of where unregulated private investment in restoration may have substantial opportunity costs or perverse outcomes for biodiversity (Crouzeilles et al., 2017). We also highlight that recently established companies focused on large-scale restoration for carbon credits are likely to compete for lands with eucalypt companies in the Atlantic Forest, which may displace carbon-focused initiatives (which may be more likely to encourage larger-scale restoration of native vegetation) towards deforested lands in the Amazon, where restoration would be less impactful in preventing species extinctions (Brancalion et al., 2019).

Despite the significance of the threats to the Atlantic Forest, potential conflicts are distributed across all biomes, most notably in the Pampas and Cerrado, suggesting the need for biome-by-biome alignment of restoration and timber production policies. Plantation expansion in grasslands, savanna and dryland habitats such as the Cerrado, Caatinga, and Pampas threaten water provisioning (Schwärzel et al., 2020), enhance fire risk, and undermine open-habitat adapted biodiversity (Bond et al., 2019; Veldman et al., 2015), with legacy effects of plantations on biodiversity extending far beyond plantation clearance (Haddad et al., 2021). In these open to less-forested ecosystems, the expansion of tree plantation may drastically change landscape functioning and undermine biodiversity conservation and ecosystem services provisioning beyond the plantation plot level. However, when limiting such plantation-restoration conflicts care must be taken avoid the risks of displacing new tree plantations to open natural habitats (Edwards, Cerullo, et al., 2021).

4.2 | Aligning restoration and production goals

Our finding that restoration priority areas are disproportionately likely to be targeted for future tree plantation expansion suggests that where restoration goals involve improving conservation outcomes rather than wood production, policies within plantation-restoration conflict areas should prioritise active or passive restoration of native habitats (Hua et al., 2022). However, without accompanying measures to meet forgone wood production, such restoration may have large unforeseen leakage effects by shifting harvests from superior-yielding tree plantations to native environments, or relegating plantations towards less-productive regions, driving greater overall plantation extent (Warman & Nelson, 2016). Although possible leakage effects from nascent habitat restoration commitments are currently poorly quantified, evidence from historic programmes in Chile and China suggests they may inadvertently increase plantation-driven habitat loss in native forests (Heilmayr et al., 2020; Hua et al., 2018). Within Brazil, leakage has already partially offset the conservation benefits of several successful environmental policies, including the soy moratorium (Villoria et al., 2022) and zero-deforestation cattle commitments (Levy et al., 2023), signalling a need for robust mechanisms that link habitat restoration with increased—and certainly not reduced—plantation production. It will also be important to integrate both restoration and plantation expansion with other land-uses and production needs (e.g. cattle and soy production etc.), to ensure that such commodities are not being displaced elsewhere, with large impacts on natural habitats (Rosa et al., 2021).

Instruments for coupling restoration with production include economic incentives or disincentives (Brancalion et al., 2017), increased crossover of restoration and forestry networks, the incorporation of additional timber certification rules that encourage limited expansion in the highest value restoration areas (Fleiss et al., 2022),

and promotion of timber yield-enhancing plantation varieties or management practices (Betts et al., 2021). Land-zoning instruments that target expansion away from high-restoration value areas may also help to navigate trade-offs, but must be carefully designed to avoid promoting unplanned plantation expansion that encourages profitability-driven rebound effects (dos Santos et al., 2020). Our models suggest areas at the sub-municipality scale where plantation expansion could potentially proceed while limiting overlap with restoration priority areas. Plantation expansion in such areas could be a critical part of meeting growing wood production needs with low biodiversity opportunity costs, thereby potentially reducing plantation conversion pressures in the highest value restoration lands. However, further work is needed to understand the social and hydrological outcomes of plantation expansion in these regions (Afonso & Miller, 2021; Coleman et al., 2021).

As mentioned above, high probabilities of plantation expansion within restoration priority areas will not always lead to conflicts, and may in places drive synergies. Certain rarely applied plantation-restoration models support substantial biodiversity and revenue creation, including in the Atlantic forest where profits from harvesting eucalypts interplanted alongside native species can cover 44%–75% of restoration implementation costs (Brancalion et al., 2020). Future counterfactual matching approaches comparing rates of native vegetation cover change between farms with and without plantation cover could investigate under which conditions, regulations, tenure systems or business models plantation expansion may contribute to rather than conflict with ecosystem restoration goals (d'Albertas et al., 2023). Yet given the substantial overlap between future plantation expansion areas and areas of the highest restoration values that we have identified, our results underscore the significant role the forestry sector in Brazil must play in lessening species extinction risk. Robust evaluations are now needed comparing whether conservation gains would be maximised by sparing areas for restoration or using forestry approaches that enhance the conservation value of plantations (Betts et al., 2021).

In conclusion, our results suggest that robust, coherent land-use policies are needed to avoid significant trade-offs between restoration and production objectives, and ensure commodity expansion does not undermine (and ideally contributes substantially towards) the most tractable conservation gains under emerging global restoration agendas. Our approach can be readily modified to incorporate expansion risk for other commodities. It can also be applied to other countries with expanding timber sectors and sizeable restoration commitments to assess the wider magnitude and severity of potential conflicts between competing restoration and production objectives.

AUTHOR CONTRIBUTIONS

Gianluca Cerullo: Conceptualization; formal analysis; investigation; methodology; writing – original draft. **Thomas Worthington:** Conceptualization; formal analysis; investigation; methodology; writing – review and editing. **Pedro Brancalion:** Conceptualization; writing – review and editing. **Joyce Brandão:** Writing – review and editing. **Francisco d'Albertas:** Investigation; methodology; writing – review and editing. **Alison Eyres:** Methodology; writing – review and editing. **Thomas Swinfield:** Investigation; methodology; writing – review and editing. **David Edwards:** Conceptualization; methodology; supervision; writing – review and editing. **Andrew Balmford:** Conceptualization; methodology; supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

All code used to generate the main results of this study is available in the following repository: https://github.com/gcerullo/Plantation_Expansion_Brazil. The publicly available data sources needed to replicate these results are provided as links in Table S1. All other data resources necessary to replicate analyses can be openly accessed from the following repository: https://doi.org/10.5281/zenodo.10650174.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.