Estimating the carbon impacts of leakage from forest restoration and the costs of reducing them

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Estimating the carbon impacts of leakage from forest restoration and the costs of reducing them

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Abstract: Ecosystem restoration is a key nature-based climate solution but risks displacing economic activities and triggering leakage – whereby forgone production drives habitat loss elsewhere, eroding benefits. Focusing on reforestation opportunities Brazilian ranchland we characterized leakage risk as the ratio of forgone beef production to carbon gained. Assuming 100% of forgone production results in extensification we asked: what is the impact of unaddressed leakage; how much can leakage be reduced by prioritizing restoration in low-yielding, high-carbon areas; and can it be cost-effectively mitigated by targeted intensification? Taking likely leakage into account but not tackling it increased median costs of restoration (over ignoring it entirely) by 43-100%, to median values of 33 and 24 USD tCO_2e^{-1} in the Atlantic Forest and Amazon, respectively. Prioritizing low-leakage sites reduced these costs by 21–37%; combining this with targeted intensification cut net carbon costs further, to 67% of unmitigated levels. Our broad findings hold at 30% (cf 100%) extensification and in other sensitivity analyses, and reveal leakage can substantially increase carbon costs, but that careful siting and targeted intensification can provide extremely cost-effective mitigation.

Introduction

Ecosystem restoration is recognized as essential for mitigating climate change[1–4] and reducing species extinctions[1]. Ambitious global restoration targets such as the Bonn Challenge, the 1 Trillion Trees initiative, and the Kunming-Montreal Global Biodiversity Framework aim to restore millions of hectares by 2030. It is important, particularly for projects financed through sales of carbon credits, that restoration efforts are additional – i.e. they would not have occurred without the intervention. Projects thus commonly restore forests on land producing agricultural or other goods. However, this creates a second challenge – the displacement of forgone production, leading to damages elsewhere. This phenomenon is known as leakage[5,6]. Leakage is typically hard to measure but is thought to be widespread, with its impacts in some cases exceeding the benefits of the intervention itself [6].

Several approaches exist to measure leakage, including general equilibrium models (e.g. Villoria et al.[7]) and quasi-experimental econometric methods (e.g. Ford et al.[8]). Yet these come with substantial limitations. Equilibrium models use economic theory and historic evidence on market behaviour to estimate where and when leakage occurs, but are highly sensitive to parameterization[5,6] and lack the resolution to identify project-level leakage impacts. Econometric approaches can identify leakage only within very limited spatiotemporal boundaries [5]. Many carbon crediting mechanisms use much simpler approaches, often involving aggregated metrics and static assumptions derived from prior research [5]. These adjustments reduce the number of credits issued to account for leakage, but often only to a very limited extent[5]. Failing to account for leakage robustly undermines the credibility of restoration-derived carbon credits[5].

Given the inherent difficulties of estimating leakage precisely, here we adopt a simpler and potentially more practical approach by exploring the implications for the amount and cost of carbon drawn down by projects, net of leakage, if all forgone production is displaced elsewhere[5], and if two complementary forms of mitigation are attempted. Using real-world data to parameterise hypothetical projects in two regions where many restoration efforts are underway, we ask three inter-related questions : (1) What is the impact of unaddressed leakage on the net carbon gain from forest restoration and how does this change the resulting cost of generating credits? (2) To what extent can leakage be reduced by prioritizing restoration in areas with high potential to store carbon but low current or potential future agricultural yields? (3) What is the scope for cost-effective leakage mitigation by actively increasing production in areas with high potential for greater agricultural yields but limited opportunities for carbon restoration? By tackling these questions in a spatially explicit framework, we hope to improve understanding of leakage from restoration and thereby enhance the credibility, robustness and cost-effectiveness of new projects.

Estimating leakage impacts

We addressed these questions in two iconic biomes that are hotspots for global restoration efforts: the Brazilian Atlantic Forest and the Brazilian Amazon[1,9]. We focused on beef due to its predominance on lands with high potential for intensification and restoration[10] and its major role in deforestation[11]. Because almost three-quarters of Brazil's beef production is consumed domestically[12], we assumed that international leakage is limited, consistent with evidence that deforestation in the Amazon is driven primarily by domestic rather than export demand[13]. Our leakage framework incorporated two key components (see Methods). First, we mapped current and potential yields of grass-fed beef to estimate (i) the forgone production from restored lands, (ii) the areas to which forgone production might plausibly be displaced, and (iii) the potential to limit displacement through spatially-targeted restoration and intensification. Second, we mapped current and potential carbon density, to evaluate (i) the additionality of restoration, (ii) the carbon impacts of displaced production, and (iii) the resulting consequences of restoration for net carbon drawdown. Combining this with data on the costs of restoration, land acquisition and intensification of grass-fed beef production we estimated carbon gains and carbon credit costs (in USD tCO_2e^{-1}), net of leakage and any mitigation. Following Filewod&McCarney[5] we make the conservative assumption that all forgone production is displaced and, if not mitigated, is met by extensification elsewhere. We also compared this conservative scenario with the default assumptions in Verra's VMD0054 protocol [14]– where only 75% of forgone production is displaced and 40% of this is met through extensification, which in combination limit extensification to 30% of forgone production.

To map beef yield we divided Brazil into a 1-km grid and generated a detailed yield layer (Supplementary Figs. 1 and 2A) combining official production [15,16] and land-use [16,17] data (details in Methods). For carbon, we developed a potential carbon gain layer as the difference between current and projected carbon densities under restoration, based on maps from Walker et al. [18]. We estimated potential carbon gains with recovery capped at 50 years – the typical timeframe for carbon-credit restoration projects (Supplementary Fig.2B), following Poorter et al. [19]. We then combined these layers to compute a forgone-production-to-carbon-gained ratio for each gridcell, indicating the likely amount of production displaced per unit of carbon gained through its restoration; spatial heterogeneity in this ratio reflects the variability in likely leakage impacts across projects. Finally, we divided our mapped surfaces into hypothetical projects (300 ha and 1700 ha in size in the Atlantic Forest and Amazon respectively, based on average project areas; see Methods).

These layers show that mean beef yield (Fig. 1A and 1C) is broadly similar between biomes, though the yield distribution is more skewed in the Atlantic Forest, where historical shifts in cattle production have resulted in a mosaic of low- and high-yielding pastures. In contrast, the more recent extensification of the Amazon[20,21] is associated with comparatively uniform yield distribution. The distributions of potential carbon gain (Fig. 1B and 1D) also vary, with higher values on the Amazon. Together these layers result in lower ratios of forgone-production-to-carbon-gained from restoration in the Amazon (mean values of 0.65 vs. 1.96 kg beef yr^{-1} tCO_2e^{-1}; Figure 1E-F), indicating lower risks of leakage from restoration; however even within the Atlantic Forest there are still many areas with potential for low-leakage restoration. In both regions favourable sites will often be low- yielding pastures undergoing intermittent regrowth[22], which in the absence of financial incentives is re-cleared before maturity [23,24]. Targeting such areas for projects has the potential to deliver highly additional, low-leakage restoration benefits.

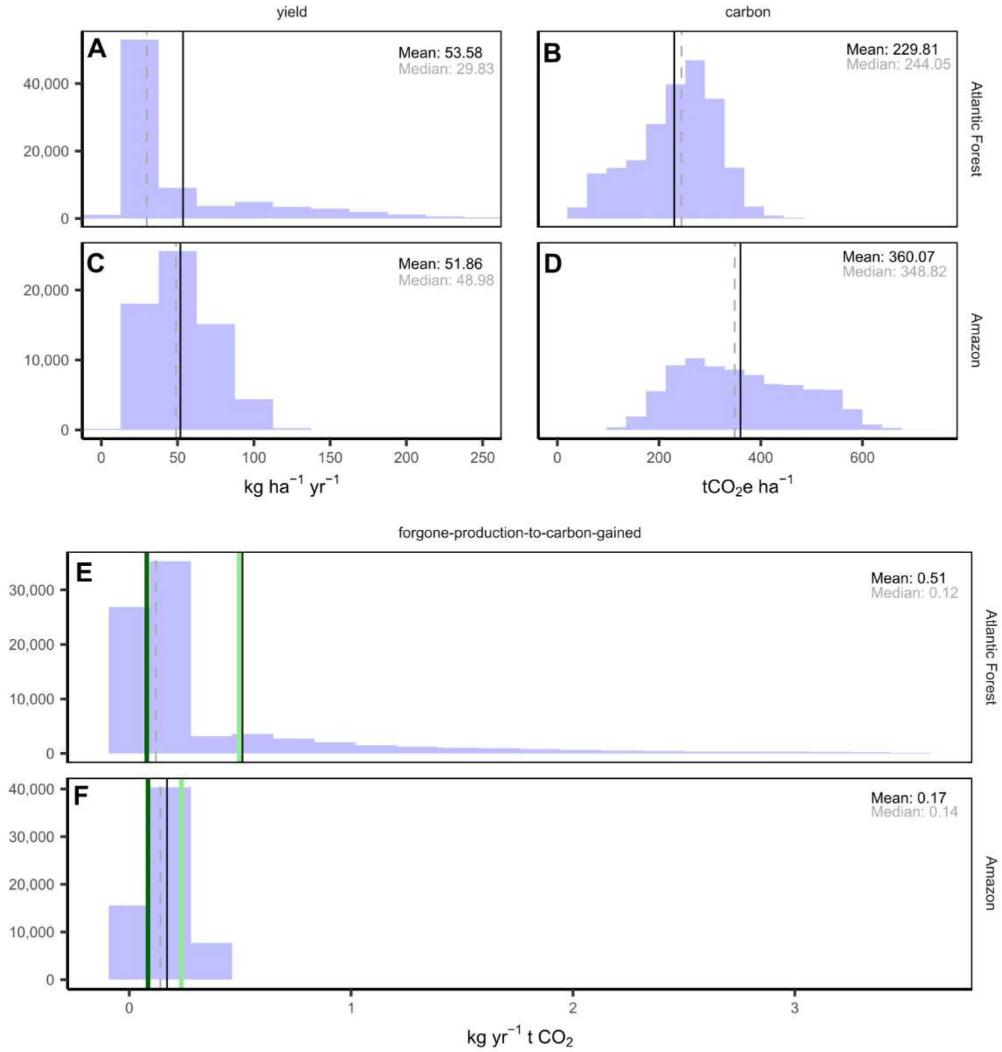

Figure 1. Distributions of beef yield, carbon gain, and forgone-production-to-carbon-gained ratios across potential project sites. Histograms show the distributions of beef yield (A,C), potential carbon gain (B,D), and the forgone-production-to-carbon-gained ratio (E,F) across potential restoration project sites in the Atlantic Forest and Amazon Forest. Solid black and dashed grey lines indicate mean and median values, respectively. We selected projects using three strategies to answer our questions: (1) we randomly drew 100 projects per biome from the full forgone-production-to-carbon ratio distribution to estimate average leakage impacts; (2) we selected 100 projects in areas with low leakage risk (dark green) and (3) 100 projects in areas with high leakage risk (light green). The latter two groups were selected from immediately above the 20th and below the 80th percentiles of the forgone-production-to-carbon-gained ratio distribution, respectively (see Methods). For visual purposes, we exclude values bellow 2.5th and above 97.5th percentiles from the distributions in figures E and F.

To investigate the implications of these patterns, we sampled 100 projects in each biome, randomly spread across the distribution of forgone-production-to-carbon-gained ratios aggregated at the project level. In determining potential carbon gains attributable to active restoration, we took account of the probability *p* that an area might anyway undergo natural regeneration (which we modelled based on proximity to forest cover and human land-uses and assuming agricultural abandonment is more likely in more remote areas[25,26]; see Methods and Supplementary Methods). Since additionality is not instantaneous, we express all emissions and removals in present-day terms by discounting future carbon fluxes (at 3% yr^{-1}, based on the Social Cost of Carbon (SCC) framework in Balmford et al.[27]; Methods). We next estimated forgone production as the expected reduction in beef output from project sites over 50 years, adjusting current yields for future growth based on trends modelled separately for each local jurisdiction in our study site from 2010-2019. To translate this into leakage, we then allocated displaced production to forest pixels outside the project by ranking pixels by their estimated likelihood of conversion to pasture[28] and by land cost[29]. We inferred the potential yield of these forest pixels from neighbouring pasture pixels and then selected them sequentially until their combined production matched the production forgone (Methods). It is of course extremely difficult to estimate where exactly leakage occurs, so to bound this uncertainty we constrained our allocation of displaced production to a series of nested domains – local, biome and country. For each domain we estimated the emissions resulting from displaced production based on woody above-ground carbon density[18]. Because cross-biome movements of cattle ranching are well documented[20,21], our main result is for the country domain. We further tested the robustness of our findings to possible international displacement by conducting a sensitivity analysis using beef yield and carbon data for other beef-exporting countries (see Supplementary Methods and Supplementary Fig. 3).

These analyses revealed that without considering leakage at all, the costs of generating carbon credits from forest restoration differ markedly across biomes, with median estimated values of 23 USD tCO_2e^{-1} in the Atlantic Forest and 12 USD tCO_2^{-1} e in the Amazon (Figure 2A). These differences were primarily driven by higher land and restoration costs in the Atlantic Forest (Extended Data Figure 1; Supplementary Fig. 2E). Taking leakage into account increased costs considerably, to 33 USD tCO_2e^{-1} in the Atlantic Forest (a 43% increase) and 24 USD tCO_2e^{-1} in the Amazon (a 100% increase) (Figure 2B). Sensitivity analyses showed that if leakage occurred within the same biome these costs would be somewhat lower (by 12% in Atlantic Forest and 21% in the Amazon), whereas assuming leakage occurred only locally increased costs by 76% and 75%, respectively (Extended Data Figure 2). But in all cases, provided all forgone production is met through extensification, in the absence of efforts to reduce leakage its impacts on net project performance and carbon costs are clearly very substantial.

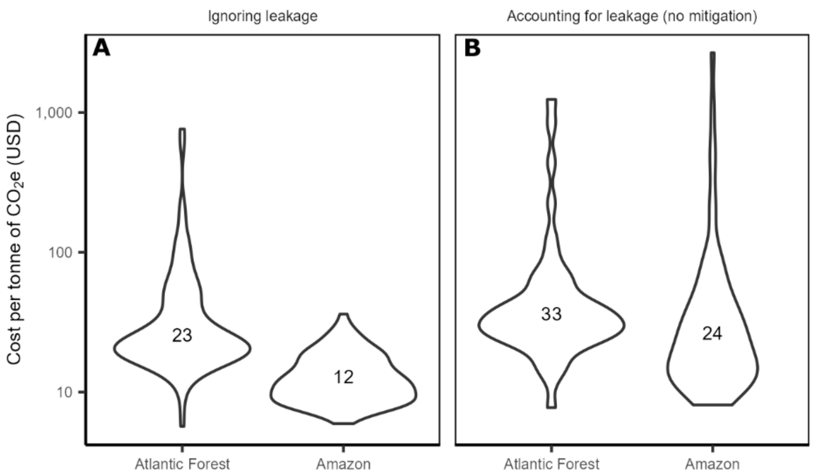

Figure 2. Effect of leakage on carbon costs of restoration projects, assuming country-domain displacement of forgone production. Violin plots show the distribution of cost tCO_2e^{-1} (in USD, log scale) for 100 restoration projects randomly selected across the forgone-production-to-carbon-gained ratio distribution in the Atlantic Forest and Amazon Forest. Numbers within plots are median values. Left panel (A) shows cost estimates ignoring leakage; right panel (B) shows estimates accounting for emissions from displaced production (assuming 100% leakage) but without leakage reduction planning or mitigation.

Addressing leakage

Turning to our second question, on the potential to reduce leakage through site selection, we found that targeting restoration towards low-leakage sites substantially reduced carbon costs. In each biome, we sampled 100 low-leakage projects (those immediately above the 20th percentile for our ratio of forgone-production-to-carbon-gained) and 100 high-leakage ones (those immediately below the 80th percentile; Methods); we excluded the tails of the distribution to produce more achievable project portfolios. We compared net carbon gain and carbon costs between these high- and low-leakage sites. In the Atlantic Forest, the carbon impacts of displaced production from high-leakage sites were so great that in net terms they caused carbon emissions, with a median loss of ~87,000 tCO_2e per project): it is this plausible that if they are not designed to avoid leakage many ranchland restoration projects could be exacerbating climate change. In contrast, low-leakage projects achieved net carbon gains, at a median cost of 26 USD tCO_2e^{-1} (Fig. 3A; cf a median of 33 USD tCO_2e^{-1} across all projects). Hence selecting low-leakage sites substantially reduced costs net of leakage. In the Amazon, high-leakage projects did on average achieve net carbon gains, but at very high cost (61 USD tCO_2e^{-1}, Fig 3C; cf 24 USD tCO_2e^{-1} for all projects). However, targeting low-leakage sites reduced carbon costs substantially, to 15 USD tCO_2e^{-1} (see Extended Data Figure 3 and Supplementary Fig. 3 for local- and biome-scale leakage domains and alternative yield trajectories). These outcomes reflect the high spatial heterogeneity in the forgone-production-to-carbon-gained ratio distribution, which is apparent across all domains considered (Extended Data Figure 4). This heterogeneity together with substantial biome differences in costs underscore the importance of project location to restoration planning and pricing.

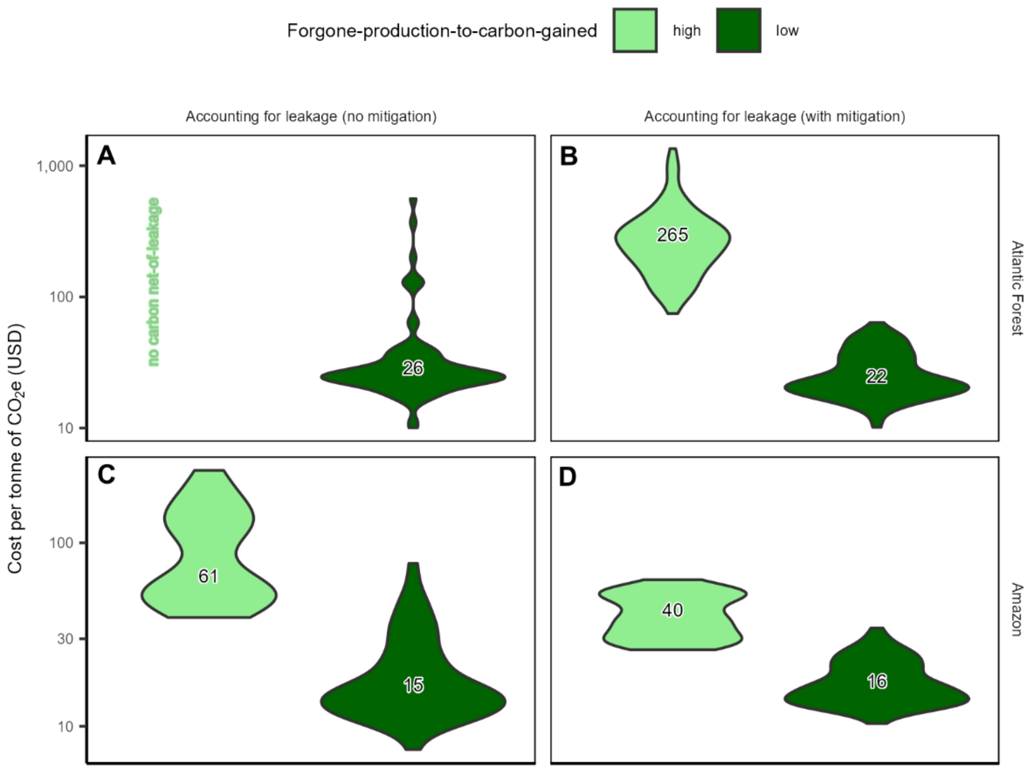

Figure 3. Effect of different leakage and mitigation scenarios on carbon costs of restoration projects, assuming country-domain displacement of forgone production. Carbon costs of restoration projects in the Atlantic Forest and Amazon under two scenarios: accounting for leakage without mitigation (A,C), and accounting for leakage with mitigation (B,D) in the Atlantic Forest and the Amazon, respectively. All results assume that 100% of forgone beef production is displaced across the country, and that mitigation actions are also undertaken at the country domain. Colours indicate high- (light green) and low-leakage (dark green) project types based on the forgone-production-to-carbon-gained ratio. Numbers represent median costs in USD tCO_2e^{-1}. Note the logarithmic scale on the y-axis.

To address our third question, we analysed how the carbon costs of our sampled projects would change if 100% of forgone production was met by targeted yield intensification elsewhere in the relevant leakage domain. Allowing for intensification to occur away from restoration locations enables more efficient land use, with project developers reforesting land of low grazing quality and cattle producers intensifying production elsewhere. We prioritised sites for mitigation using a modified version of our ratio between production and carbon, now reflecting the production-gained-to-carbon-forgone for each site currently under pasture (see Methods). Each site's potential yield gain from intensification was calculated as the difference between its current yield and 90% of its estimated grass-fed carrying capacity, again adjusting for the possibility of land abandonment whereby current yields have a probability *p* (as above for restoration sites) of falling to zero (see Methods). We estimated the forgone carbon from intensification as a carbon opportunity cost, calculated as the product of *p* and the possible carbon gains if forest regenerated naturally (Methods). We ranked all pasture sites within the leakage domain of our restoration projects in order of decreasing production-gained-to-carbon-forgone, capped the distribution at the 80th percentile, and allocated mitigation to the most efficient areas by selecting them sequentially until all forgone production was met. Lastly, we estimated mitigation costs using state-specific intensification costs (see Supplementary Table 2 and Methods) and added these to restoration-site costs to estimate overall carbon costs for fully-mitigated restoration projects.

Actively mitigating leakage consistently reduced carbon costs across most settings, except for low-leakage sites in the Amazon, where mitigation led to a marginal (~1 USD tCO_2e^{-1}) increase relative to accounting for leakage without mitigation (Figure 3B and 3D). For projects in low-leakage sites, overall carbon costs accounting for but then fully mitigating leakage were 33% less than the median costs without site targeting or directed intensification (22 cf 33 USD $tCO2e^{-1}$ for the Atlantic Forest and 16 cf 24 USD $tCO2e^{-1}$ for the Amazon; Supplementary Table 4). Although mitigation increases total costs (Extended Data Figure 6), these increases are far less than the gains in net carbon drawdown achieved by fully mitigating leakage (Extended Data Figure 6). These results also hold when leakage and mitigation occur at local and biome domains, although mitigation is costlier for the local domain because the choice of mitigation sites is more constrained (Figure 4 and Extended Data Figure 3). Our finding that mitigation is highly cost-effective again results from the very large variation in forgone-production-to-carbon-gained within all domains, and because of a second important asymmetry: for our study regions the costs of beef intensification are much lower than the costs of restoration (Extended Data Figure 7).

Sensitivity to assumptions

Our central findings – that if unaddressed, leakage drives up carbon costs very considerably, but that careful selection of restoration and mitigation sites can greatly reduce these impacts – are robust to variation in the spatial domain we assume for leakage, intensification and yield growth projections (see Figure 4**,** Extended Data Figure 3 and 4**,** Supplementary Methods, and Supplementary Figs. 3-4). We considered two further important uncertainties. First, we calculated carbon costs using discount rates for the SCC from 2-4%. Absolute values varied with the rate adopted – for example, shifting from 2 to 4% yr^{-1} increased carbon costs in the mitigation scenario from 22 to 24 USD tCO_2e^{-1} and from 15 to 17 USD tCO_2e^{-1} for low-leakage sites in the Atlantic Forest and Amazon, respectively (Extended Data Figs. 8A-8C, 9A-9C; Supplementary Table 4). However, targeted restoration combined with leakage mitigation remained highly cost-effective. In a further sensitivity test we compared results assuming that all or only a modest (30%) share of forgone production results in extensification. Again, targeted site selection combined with mitigation was always more cost-effective than not addressing leakage (Extended Data Figs. 8D and 9D). Strikingly, under mitigation combined with targeted restoration of low-leakage sites, assuming only 30% (rather than 100%) of forgone production led to extensification had little impact on net carbon costs, reducing them from 22 to 21 USD tCO_2e^{-1} in the Atlantic Forest and 16 to 12 USD tCO_2e^{-1} in the Amazon. For project developers and their clients, making credits substantially more robust by adopting much less risky assumptions about the magnitude of leakage would thus seem to have little impact on carbon prices.

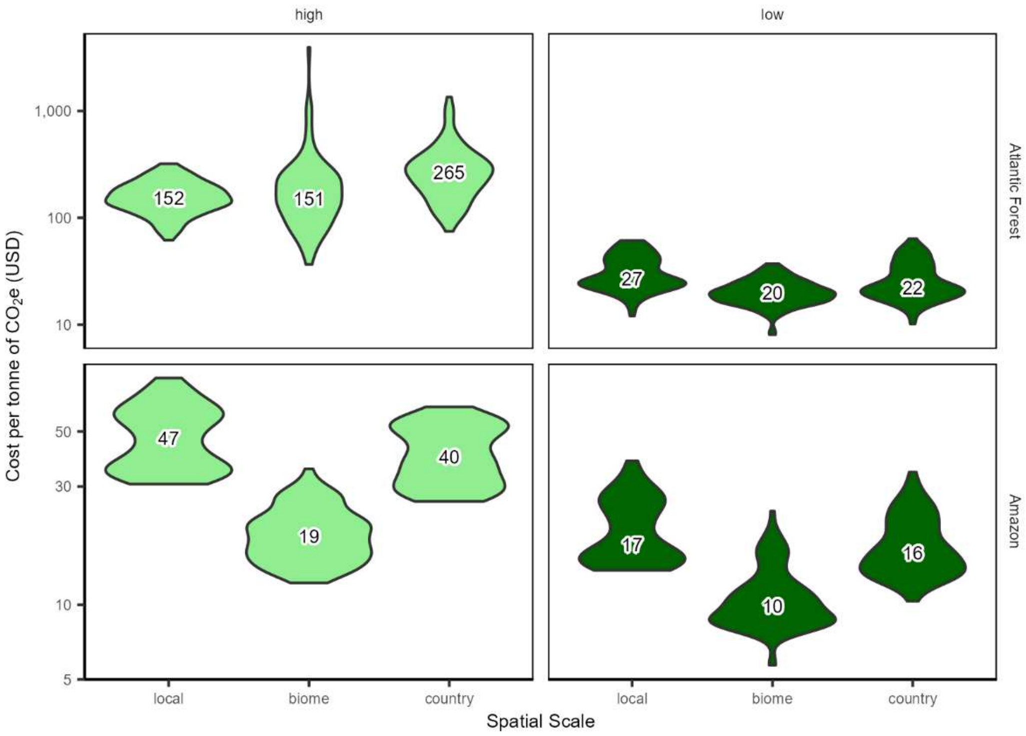

Figure 4. Effect of different assumptions about the spatial scale of leakage and mitigation on carbon costs of restoration projects. Violin plots show the distribution of carbon costs incorporating leakage mitigation through compensatory off-site intensification of beef production (USD tCO_2e^{-1}) across three assumed domains for leakage and mitigation: local, biome, and country. Panels reflect combinations of biome (Amazon vs. Atlantic Forest) and leakage intensity (high vs. low leakage sites). Numbers indicate median costs for each group.

Discussion

We quantified the impact of leakage and of different strategies to address it and evaluated their influence on the costs of generating carbon from Brazilian cattle ranches. We find that once leakage is considered, without mitigation net carbon gains are significantly reduced, markedly increasing the cost of carbon drawdown. Unless leakage is properly accounted for, climate benefits claimed and sold are likely to substantially exceed what is actually achieved – indeed for high-leakage sites restoration might quite plausibly cause net harm to the climate. Thus, ignoring leakage would be a costly oversight borne both by project developers and buyers – who face, at a minimum, reputational risk if inconsistencies are revealed – and by society at large, if overstated carbon gains are used to offset carbon emissions. However, leakage effects can in principle be addressed and mitigated. Project location is critical: targeting restoration towards areas that displace less production and have greater potential to store carbon (i.e. low-leakage sites) can substantially reduce leakage and thus net carbon costs. Further, we show that active mitigation – investing in pasture intensification in regions with high potential for yield increases at low carbon opportunity cost – can further reduce net carbon costs. These findings hold in both the Amazon and Atlantic Forest and across all leakage and mitigation domains, as well as different yield trajectories, discount rates and assumptions about how far forgone production leads to extensification. They arise because of pronounced spatial heterogeneity in forgone-production-to-carbon-gained ratios across the Brazilian beef sector (Extended Data Fig. 4), and because forest restoration is typically far costlier than intensification (Extended Data Fig. 7).

Implications for understanding and mitigating leakage

Efforts to quantify leakage from conservation interventions[30] have so far produced highly variable estimates. For example, Villoria et al.[7] estimated 43-50% leakage of deforestation under Brazil's Soy Moratorium, while Alix-Garcia et al.[31] reported that leakage largely undermines the benefits of Brazil's zero-deforestation cattle agreement. By contrast, looking in the vicinity of projects Ford et al.[8] found mixed outcomes, detecting both increased deforestation (leakage) and reductions (blockage) beyond treatment areas. Guizar-Coutiño et al.[32] found no evidence of local leakage from REDD+ projects, while Daigneault et al.[33] reported highly variable leakage; blockage has also been reported by Barros et al[34].

However, these results often depend on assumptions about price elasticities and market responses, or the idea that production is only displaced to nearby buffer zones and not more broadly. As we show here, uncertainty in defining the relevant leakage domain can change estimates of leakage impacts by 35–70% (Figure 4). Given these divergent findings and their methodological limitations, for our central estimates we follow Filewod & McCarney[5] in assuming that in the absence of strong evidence otherwise, all forgone production is met through extensification elsewhere. However, we also note that much more lenient assumptions have little impact on the costs of carbon drawdown by judiciously-located projects.

Our work complements existing methods by avoiding commercially favourable but potentially questionable assumptions about market or behavioural responses to carbon projects and instead quantifying the consequences of a simple, conservative assumption about leakage. This approach yields robust ex ante guidance on where leakage risks are greatest, how far they can be minimised through project siting, and where mitigation is most cost-effective. This can help project developers limit leakage by design. In principle our framework could be further refined through ex post quasi-experimental evaluations of leakage, once interventions are underway, allowing credit issuance to be adjusted in light of empirical evidence. But basing such adjustment on a conservative ex ante approach reduces the risk of over-issuing credits and ensures that any ex-post correction is more likely to increase, rather than decrease, the volume of credits a project can issue.

Limitations

Our methods are of course limited, in several ways. First, we assume changes in cattle production are instantaneous, whereas in practice, both extensification and intensification are incremental processes which are likely to unfold over different timeframes. Depending on which occurs more rapidly, our assumptions could either overestimate or underestimate the net effects of leakage and mitigation. Second, our results depend on how leakage is allocated spatially. Alternative allocation approaches would shift the spatial distribution of leakage, but the robustness of our findings to widely divergent assumptions about market domains suggest such differences would not alter our main qualitative conclusions. Third, we do not account for the fact that intensified systems emit less greenhouse gases per unit of beef produced[35,36], and as a result we underestimate the climate benefits of active mitigation through intensification; if such efficiencies were rewarded through carbon pricing this would further reduce the mitigation costs set out here. Fourth, to allow for large-scale analysis of the extent of leakage and how it might be tackled, our data on carbon additionality, forgone production and yield intensification are relatively coarse; this is appropriate for developing a strategic framework but practical implementation would necessitate site-specific data on carbon fluxes, yields and costs, as well as ex post quasi-experimental evaluations of the additionality of restoration and intensification interventions[37,38]. Finally, our model assumes leakage arises solely because of the displacement of production. The leakage reduction strategies we explored would be less effective if rancher-driven extensification is motivated primarily by land speculation to secure land claims[13]. However, to the extent that such speculation is ultimately driven by cattle ranching, it would still be captured within our framework. Several lines of evidence suggest cattle production is the primary motivation for leakage in our study system: cattle ranching is the dominant cause of deforestation in Brazil[11], deforestation patterns vary with beef prices [39,40], and expanding pasture by clearing forest remains more profitable than intensifying existing pasture in many regions [41–43]. Given this context, we believe intensifying beef production beyond restoration sites is a robust leakage mitigation strategy.

Generality of our results

How far are our findings here likely to apply to other natural climate solutions and production systems? This will depend on the level of heterogeneity in forgone-production-to-carbon-gained ratios, on how the costs of achieving carbon gains (through restoration or avoided emissions) compare with those of intensification, and on the availability of both low-leakage project sites and suitable areas for mitigation within the domain under consideration. We suggest future work could usefully examine whether these conditions are met in other regions and production systems which are potentially amenable to restoration. This will require reasonably robust data on production, carbon stocks and intervention costs, which are not yet available for all production systems and natural climate solutions. One further promising avenue would be to investigate whether restoration and intensification can be jointly planned within individual sites[5] – identifying parts of properties suitable for cost-effective restoration while simultaneously intensifying production on remaining land.

In summary, if carbon credits are to be regarded as a credible nature-based solution to the climate crisis, their integrity must be beyond reproach. Our results show that tropical forest restoration in ranching landscapes can deliver highly cost-effective climate benefits – but only when leakage risk is acknowledged, accounted for, and explicitly minimized. Achieving this requires shifting attention beyond tree planting itself to the drivers of deforestation that determine whether restoration delivers carbon net gains. By integrating restoration with strategies that reduce or compensate for displaced production, natural climate solutions can more reliably realize their full climate mitigation potential[44,45].

Methods

Our framework followed six main steps (Figure 5): (A) calculating a forgone-production-to-carbon-gained for each 1-km^2 pasture cell to quantify potential leakage if restored; (B) selecting 100 random and 200 targeted projects per biome to evaluate average, high-, and low-leakage outcomes; (C) estimating forgone production, its consequences if not addressed, and scope for its mitigation; (D) computing total project costs from costs of land acquisition, restoration, and (where applicable) mitigation; (E) calculating net carbon balance; and (F) deriving net carbon costs (USD tCO_2e^{-1}). All spatial layers were harmonized to 1-km resolution in the Albers Equal Area Conic projection. For leakage and mitigation, we considered three nested domains: local (clusters of municipalities that share strong socioeconomic and geographic ties, particularly around a central urban hub[46]), biome, and country (Supplementary Fig. 2F). All analyses were conducted in R [47] using the most recent data available.

A. Potential for leakage

Defining project sizes

We used the latest Census of Agriculture [48], reporting the number and area of legal rural properties per municipality across 17 size classes as defined by IBGE (Brazilian Institute of Geography and Statistics) (Supplementary Table 1). Mean property sizes were approximately 1,700 ha in the Amazon and 300 ha in the Atlantic Forest biome (details in Supplementary Methods). We then defined potential projects by clustering 1km^2 pasture pixels within each biome to match average project sizes – three pixels (totaling 300 ha) in the Atlantic Forest and 17 (1700 ha) in the Amazon, excluding isolated pasture pixels.

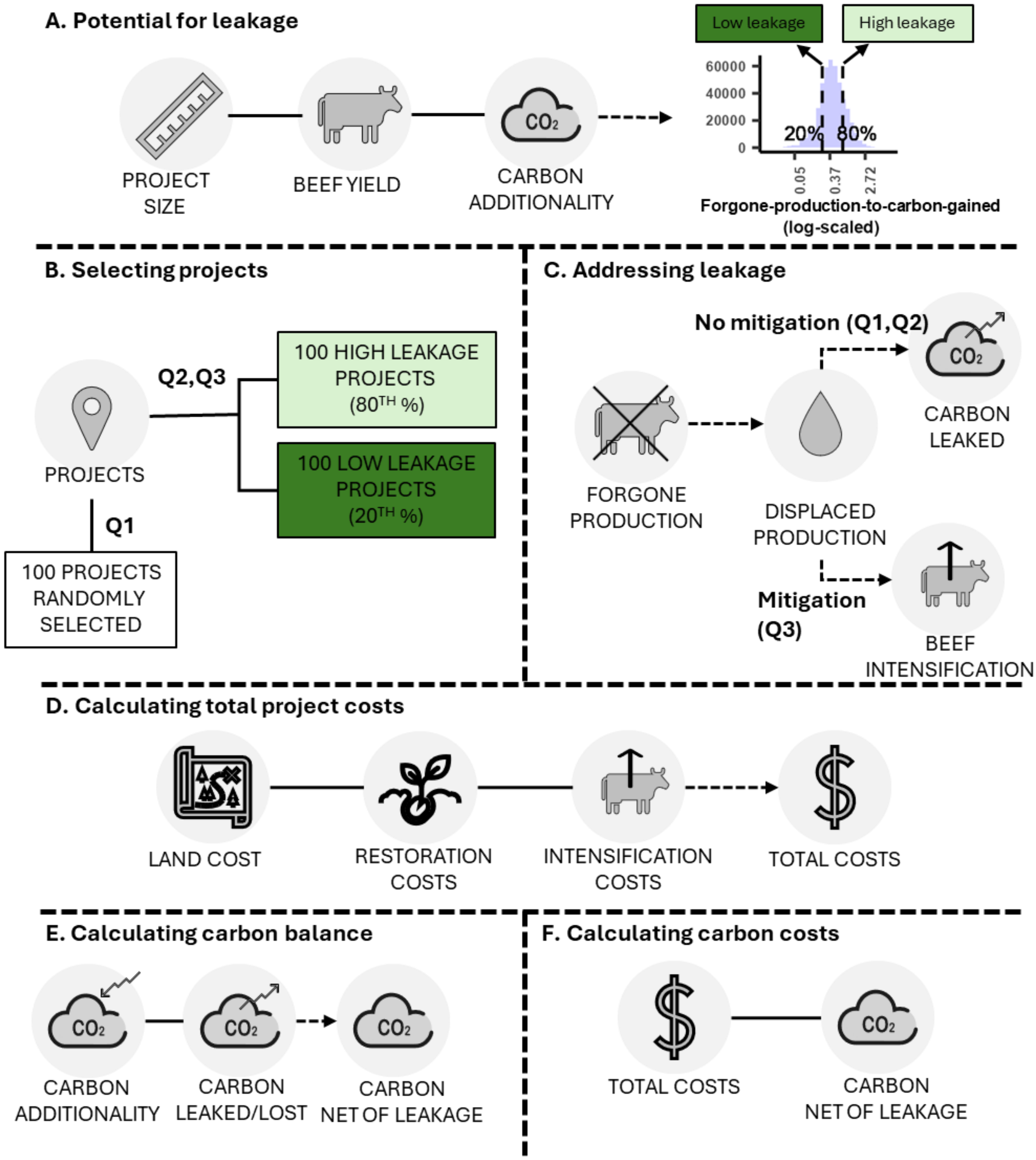

Figure 5. Workflow to assess the impacts of leakage from restoration. (A) After defining candidate restoration projects reflecting typical property sizes (Atlantic Forest = 300 ha; Atlantic Forest = 1,700 ha), we quantified their potential for leakage by calculating the ratio between current beef yield (kg ha^{-1} yr^{-1}) and carbon additionality (tCO_2e ha^{-1}), the forgone-production-to-carbon-gained ratio. This describes how much production a restoration project is likely to displace per unit of carbon gained. (B) We selected projects using two strategies: (Q1) randomly drawing 100 projects per biome from the full distribution of ratio values to estimate average leakage impacts; and (Q2 and Q3) selecting 200 projects per biome–100 immediately above the 20^{th} percentile (low leakage) and 100 just below the 80^{th} (high leakage). (C) For each project, we estimated forgone production (kg) by adjusting current yields according to projected growth over 50yr, and from that the resulting carbon leakage arising from displacement to current forest areas (for Q1 and Q2) or the carbon opportunity cost of forgone natural regeneration due to compensatory yield increases in mitigation areas already under pasture (Q3). (D) We calculated total project costs (USD) by summing expenses from land acquisition, restoration, and intensification. (E) We computed net carbon balance as additionality minus leakage (when there is no mitigation) or minus the carbon lost due to forgone natural regeneration of mitigation sites. (F) We derived CO_2e costs by dividing total costs by the net carbon balance.

Carbon additionality

We obtained current and potential carbon stocks—aboveground, belowground, and soil organic carbon—from Walker et al. [18]. Since recovering tropical forests typically do not reach full biomass within 50 years, we adjusted potential carbon stocks using a biomass recovery curve from Poorter et al[19]. First, we extracted aboveground biomass recovery (% of old-growth biomass) using WebPlotDigitizer (https://automeris.io/). This indicates that after 50 years, biomass recovers to 86.9% of old-growth levels (Supplementary Fig. 5). Then, we scaled the potential carbon stock layer to reflect the biomass expected after 50 years of recovery. Next, for every cell *c* from project *pj* we calculated the carbon additionality of restoration of that cell ($C_{a[c,pj]}$, in tCO_2e) as the difference between its potential ($C_{p[c,pj]}$; tCO_2e ha^{-1}) and current carbon density ($C_{c[c,pj]}$; tCO_2e ha^{-1}) (Supplementary Fig. 2B), adjusted by its probability *p* of undergoing regeneration naturally as a result of land abandonment (see *Restoration costs* section below, and Supplementary Methods), all multiplied by the area restored($a_{[c,pj]}$in ha):

$$C_{a[c,pj]} = \left(C_{p[c,pj]} - C_{c[c,pj]}\right) \cdot \left(1 - p_{[c,pj]}\right) \cdot \ a_{[c,pj]} \qquad (2)$$

We derived *p* following Williams et al. [25] model, using the same set of co-variates (e.g. climate, land use) but retraining the model for Brazil. The binary response indicated whether natural regeneration occurred in each 1-km pixel, defined as a transition to secondary vegetation according to the MapBiomas classification between 2000 and 2022[49] . Full details are in Supplementary Methods (see Supplementary Table 6 for cost details, Supplementary Figs. 6 for model performance, Supplementary Fig. 2D for natural regeneration probability map and Supplementary 2E for the final cost map).

Forgone-production-to-carbon-gained ratio calculation

We calculated the ratio of forgone-production-to-carbon-gained for each 1-km^2 pasture cell across Brazil. This ratio provided an indication of the likely forgone production arising from restoring its carbon stocks (Figure 5A**)**.

B. Selecting projects

For each project, we calculated the mean forgone-production-to-carbon-gained. Then, to answer our first question about the impacts of leakage from average projects, we randomly selected 100 projects across the full production-to-carbon distribution in each biome. For our second and third questions (selecting sites to limit leakage, and mitigating leakage through off-site intensification), we restricted selection to projects between the 20^{th} and 80^{th} percentiles of this distribution, ranked them by their mean ratio and selected the 100 lowest- and 100 highest-ranking projects per biome (Figure 5B).

C. Addressing leakage

Leaked forgone production

To calculate the annual forgone production accounting for future yield trends (Figure 5C**)**, we projected beef yields to year (*t*) 50, representing expected production levels at the end of the project period. We calculated final project (*pj)* cell yields ($Y_{f[c,pj]}$, in kg ha^{-1} yr^{-1}) as:

$$Y_{f[c,pj]} = Y_{c[c,pj]} \cdot \left(1 + t \cdot (max(0, g_{[l]})\right) \quad (3)$$

and each project's forgone production (*FP*, in kg carcass weight yr^{-1}) as:

$$FP_{[pj]} = \sum_{c=1}^{Ncells} \mathrm{Y}_{\mathrm{f[c,pj]}} \cdot a_{[c,pj]} \quad (4)$$

where $Y_{c[c,pj]}$ is the current yield at cell *c*, $g_{[l]}$ is the annual beef yield growth at each local jurisdiction *l* where projects are located, and $a_{[c,pj]}$ is the area (ha) restored. Note that if it is currently negative this formulation sets yield growth to zero, to avoid underestimating future forgone production. To avoid overestimation, $\mathrm{Y}_{\mathrm{f[c,pj]}}$ was capped at 90% of local carrying capacity following Strassburg et al.[10] (see Supplementary Methods and Supplementary Fig. 2C). We also ran two sensitivity tests assuming constant yields, and assuming all projects reach their carrying capacity (Supplementary Fig. 3).

Annual leaked forgone production (*LFP; kg carcass weight yr*$^{-1}$) was then estimated as:

$$LFP_{[pj]} = FP_{[pj]} * l \tag{5}$$

with $l = 1$ in our main analysis (100% leakage) and $l = 0.3$ in a sensitivity scenario based on Verra's VM0054 methodology.

Quantifying leaked carbon

To estimate carbon emissions from unmitigated displacement (Figure 5C) we assigned extensification at the cell level to forests within the relevant domain. For each project, we allocated forgone production to individual forest cells by ranking them in decreasing order of probability of conversion to pasture[28], and, in case of ties, by lower land value[29]. We therefore assume that extensification is most likely to occur where conversion risk is higher and land is cheaper. We estimated the yield and hence production of each pixel following its conversion to pasture from 2021 mean yield values of surrounding pasture cells, using a 9×9 moving window. We selected forested pixels until their combined production matched the leaked forgone production from the project. For the same set of pixels, we extracted current above-ground woody carbon density (t carbon ha^{-1}) from Walker et al.[18] converted to CO_2 using a factor of 44/12, and summed to obtain total CO_2e lost (assuming that the resulting pastures have no woody biomass).

Selecting areas for mitigation

To pick areas for mitigating leakage through intensification, for each non-project cell c in the relevant domain with >1% degraded pasture we extracted current beef yield and yield at carrying capacity. We then estimated intensified yields at the cell level using spatially explicit outputs from the BeefSC model[50], which simulate production under improved pasture management, capped at carrying capacity (Supplementary Methods). Total yearly added production was calculated as:

$$P_I = \sum_{c \in mitigation} a_{m[c]} \cdot \left[p_{[c]} \cdot \mathrm{Y}_{\mathrm{I}[c]} + \left(1 - p_{[c]}\right) \cdot \left(\mathrm{Y}_{I[c]} - Y_{C[c]}\right)\right] \tag{6}$$

where P_I is the intensified production (kg carcass weight of beef yr^{-1}), $a_{m[c]}$ is the pasture area available for mitigation (in ha), $Y_{I[c]}$ and $Y_{C[c]}$ are intensified and current beef yield at the mitigation areas (in kg carcass weight ha^{-1} yr^{-1}), respectively (Figure 5C) and the summation is taken over all selected cells within the mitigation domain. The term *p* incorporates the expected share of the land that would otherwise naturally regenerate and cease cattle production: as a result of intensification (which prevents regeneration) production rises from 0 to Y_I on that fraction and from Y_C to Y_I on the remainder (1-p).We estimated the carbon lost from intensification in each cell as the forgone opportunity for natural regeneration:

$$C_{fg} = \sum_{c \in mitigation} \left(\mathrm{C}_{\mathrm{p[c]}} - \mathrm{C}_{c[c]}\right) \cdot a_{m[c]} \cdot p_{[c]} \tag{7}$$

where C_{fg} is the forgone carbon from mitigation sites (in tCO_2e), $\mathrm{C}_{\mathrm{p[c]}}$ is the potential carbon density in cell c (tCO_2e ha^{-1}) and $\mathrm{C}_{c[c]}$ is the current carbon density in cell c (tCO_2e ha^{-1})

We then computed the ratio of production-gained-to-carbon-forgone for each candidate pasture cell, ranked them all within each domain from highest to lowest for this new ratio, discarded cells above the 80th percentile (to avoid assuming intensification could be achieved in near-optimum areas) and selected cells sequentially until all forgone production from projects was met.

D. Calculating total project costs

We calculated total project costs as the sum of land value, restoration costs, and intensification costs (Figure 5D). All monetary values were adjusted to constant 2021 Brazilian reais using the accumulated Broad National Consumer Price Index (IPCA) and converted to US dollars using the 2021 average exchange rate (available from the Central Bank of Brazil: https://www.bcb.gov.br/).

Land value

We used land prices from a dataset that interpolated publicly available data from the Brazilian Government into a continuous land value surface for Brazil, with estimates for the year 2023 [29].

Restoration costs

Restoration cost estimates were based on data provided by re.green, a Brazilian project developer. Costs vary by biome, regeneration potential, and feasibility of mechanization. We adjusted cost spatially using natural regeneration probability *p* and assumed mechanization only on slopes ≤ 20% (Supplementary Equation S12).

Intensification costs

We estimated annual beef intensification costs from better pasture management using yield gains and associated costs to improve low and medium vigour pasturelands from Wirsenius & d'Albertas [50] (Supplementary Table 2). Costs were assigned to each pasture cell by state and vigour level. We then calculated the net present value of long-term intensification over 50 yr, assuming an 8% discount rate (details in Supplementary Methods).

E. Calculating carbon balance

For each project we computed the net undiscounted carbon balance at year *t* ($C^{und}_{[t,pj]}$; in tCO_2e) as carbon additionality ($C_{a[t,pj]}$) minus leakage ($C_{leak[t,pj]}$) and, under mitigation, minus the carbon lost from the forgone possibility of natural regeneration of intensified areas ($C_{fg[t,pj]}$) (Figure 5E). All carbon terms are expressed at the project level and were obtained by summing the corresponding cell-level quantities across all cells belonging to each project *pj* at each year *t*:

$$C^{und}_{[pj,t]} = C_{a[t,pj]} - \left(C_{leak[t,pj]}, C_{fg[t,pj]}\right) \quad (8)$$

Leakage was assumed to occur entirely in year one, whereas carbon accumulation followed a biomass recovery trajectory (Supplementary Fig. 5). To compare these time-differentiated fluxes, we weighted annual net carbon fluxes by the Social Cost of Carbon (SCC), following the schedule and method in Balmford et al. [27], allowing the

SCC to evolve with economic growth (1.7% yr^{-1}), with climate damages increasing quadratically with temperature according to RCP 4.5 and assuming a 3% discount rate. For each year t, we then multiplied the annual undiscounted net carbon balance $C_{[pj,t]}^{und}$ by a ratio R_t, defined as the discounted SCC in year t divided by its 2021 value, and then summed the product across years to obtain the discounted net carbon balance:

$$C_{pj}^{disc} = \sum_{t=0}^{T} R_{[t,pj]} \cdot C_{[pj,t]}^{und} \tag{9}$$

where C_{pj}^{disc} is the total discounted net carbon balance in present value terms. We set T at 50 years to derive a cumulative, time-weighted measure of net carbon over the project's lifetime (details in Supplementary Methods).

We also tested alternative discount rates (2% and 4%; see Supplementary Methods and Supplementary Fig. 7).

F. Calculating carbon costs

We calculated carbon costs (in USD tCO_2e^{-1}) by dividing the total project costs by the total present value of the net carbon balance under each leakage scenario (Figure 5F).

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Declaration of interests

S. Mortara and D. Martins are affiliated with companies working on forest restoration and nature-based solutions (re.green and Earthshot Lab, respectively).

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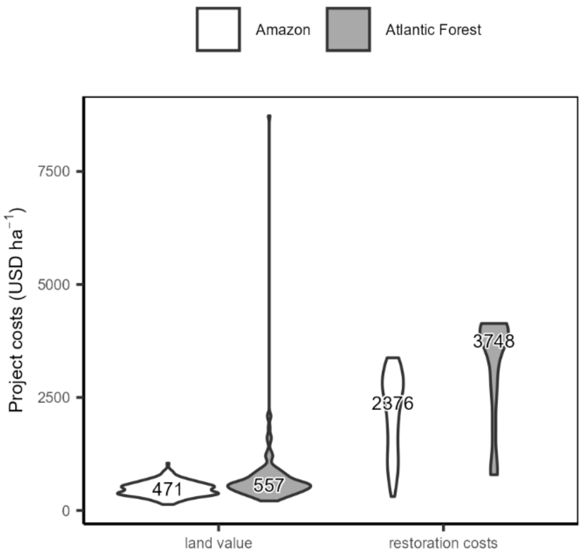
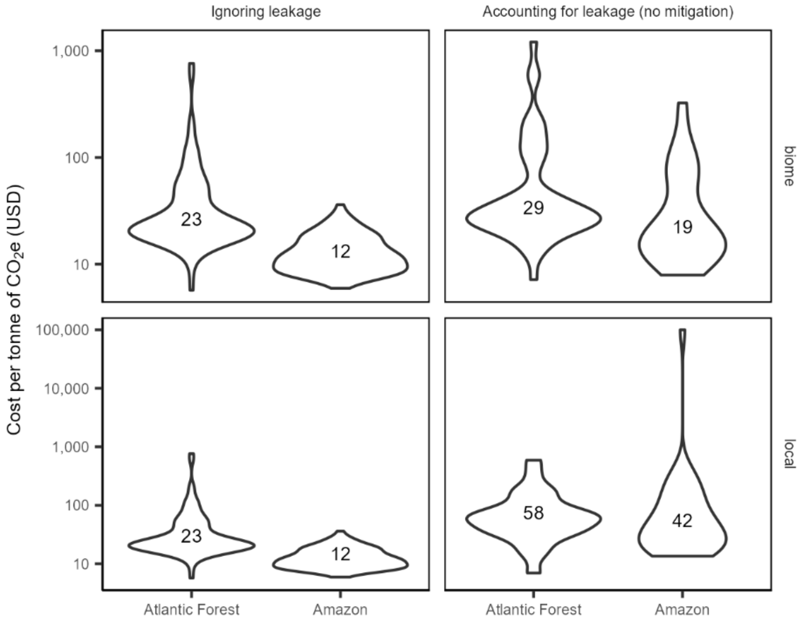
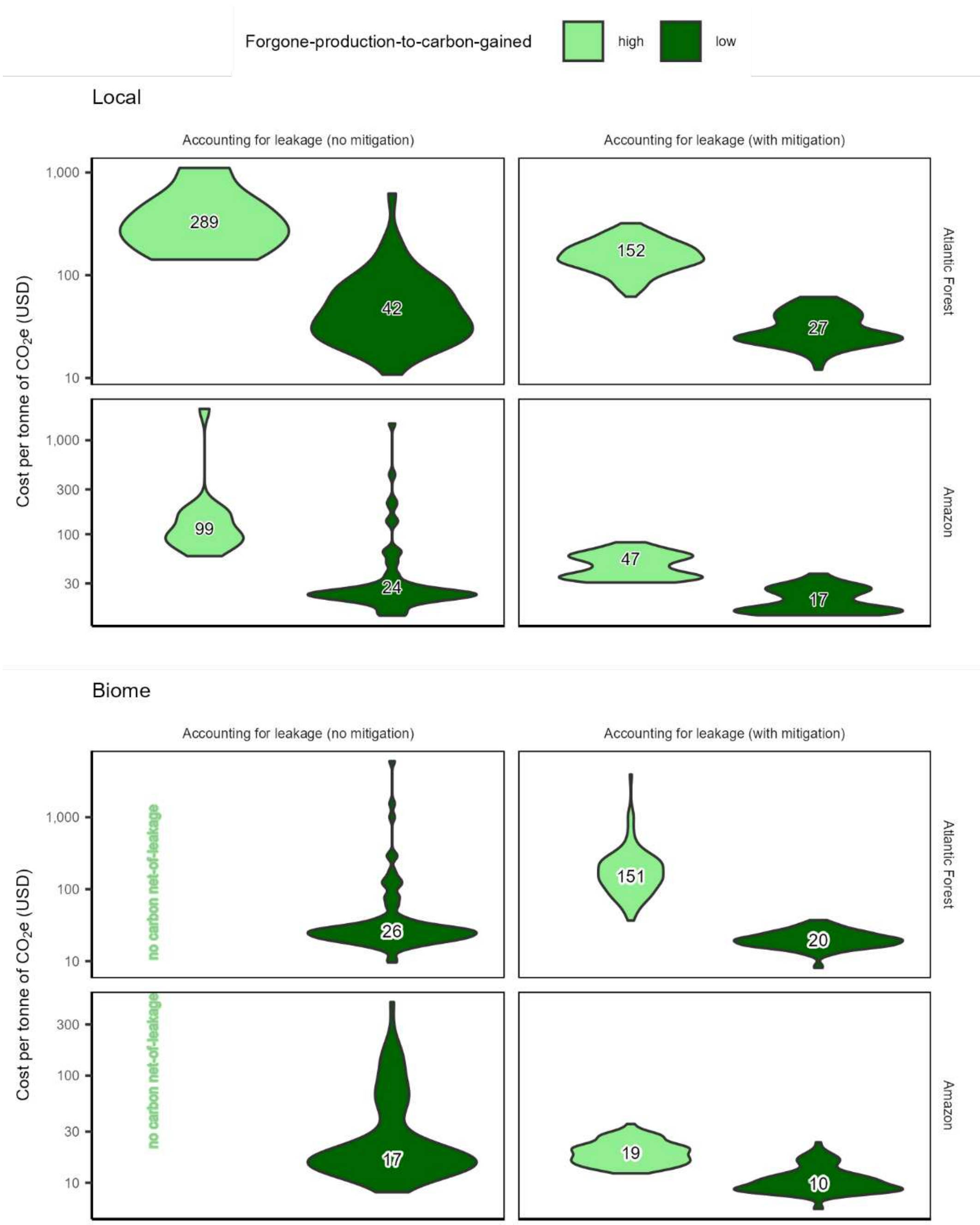
Extended Data Figures



Extended Data Figure 1. Variation in land value and restoration costs across biomes. Violin plots show the distribution of land value and restoration costs (USD ha^{-1}) for 100 restoration projects randomly selected across the forgone-production-to-carbon-lost ratio distribution in the Amazon (white) and Atlantic Forest (grey). Median values are indicated numerically.



Extended Data Figure 2.Carbon costs for projects allocated at random under different leakage scenarios assuming local or biome-scale displacement. Violin plots show the distribution of cost per tonne of CO_2e (in USD, log scale) for 100 restoration projects randomly selected across the forgone-production-to-carbon-lost ratio distribution in the Atlantic Forest and the Amazon. Median values are indicated numerically. Left panel shows cost estimates ignoring leakage; right panel shows estimates accounting for emissions from displaced production (assuming 100% leakage) but without mitigation. Note the logarithmic scale on the y-axis.



Extended Data Figure 3. Carbon costs under different leakage and mitigation scenarios assuming local or biome-scale displacement. Carbon costs of restoration projects in the Atlantic Forest and the Amazon under two scenarios for local (upper panel) or biome-level (bottom panel) displacement: accounting for leakage without mitigation, and accounting for leakage with mitigation. All results assume that 100% of forgone beef production is displaced within the same domain where the project occurs, and that mitigation actions are also constrained to that domain. Colours indicate project types based on forgone-production-to-carbon-gained ratio: light green for high ratio values (higher leakage potential) and dark green for low ratio values (lower leakage potential). Numbers represent median costs in USD per tCO_2e. Note the logarithmic scale on the y-axis.

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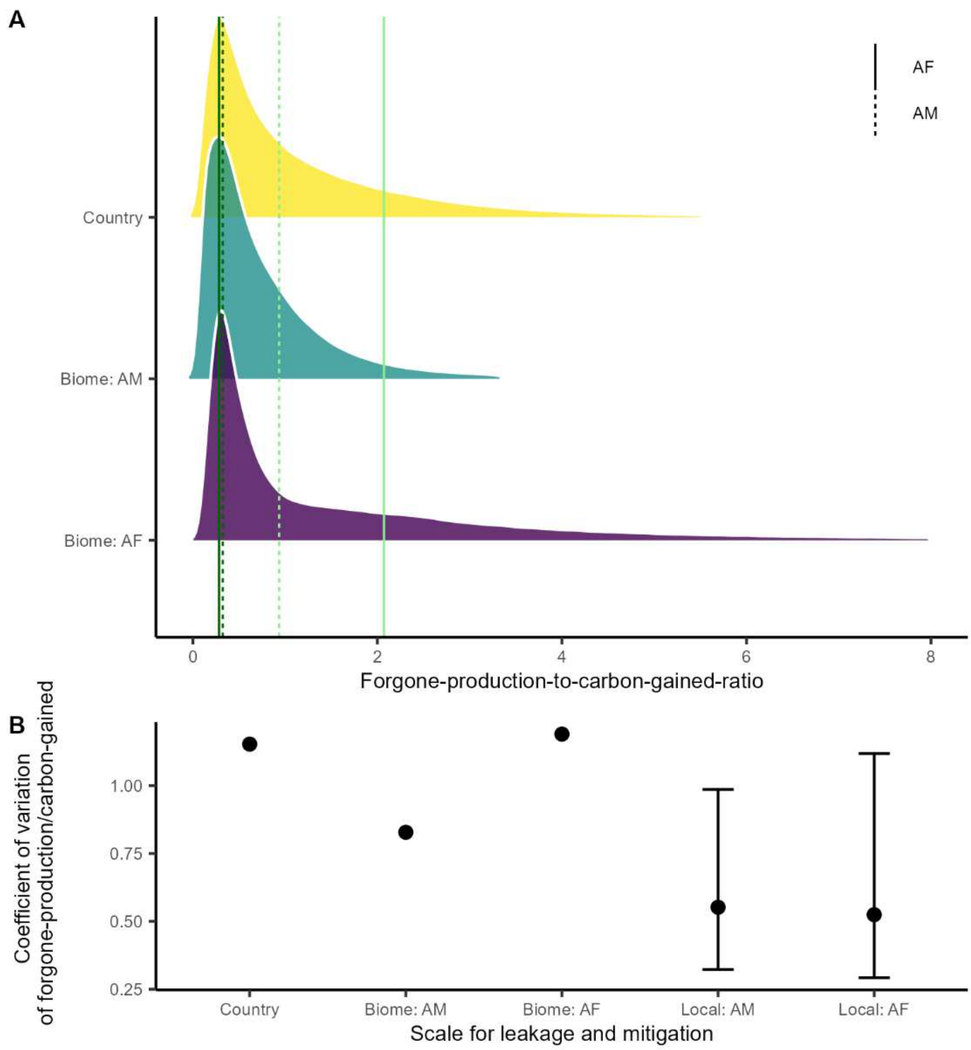
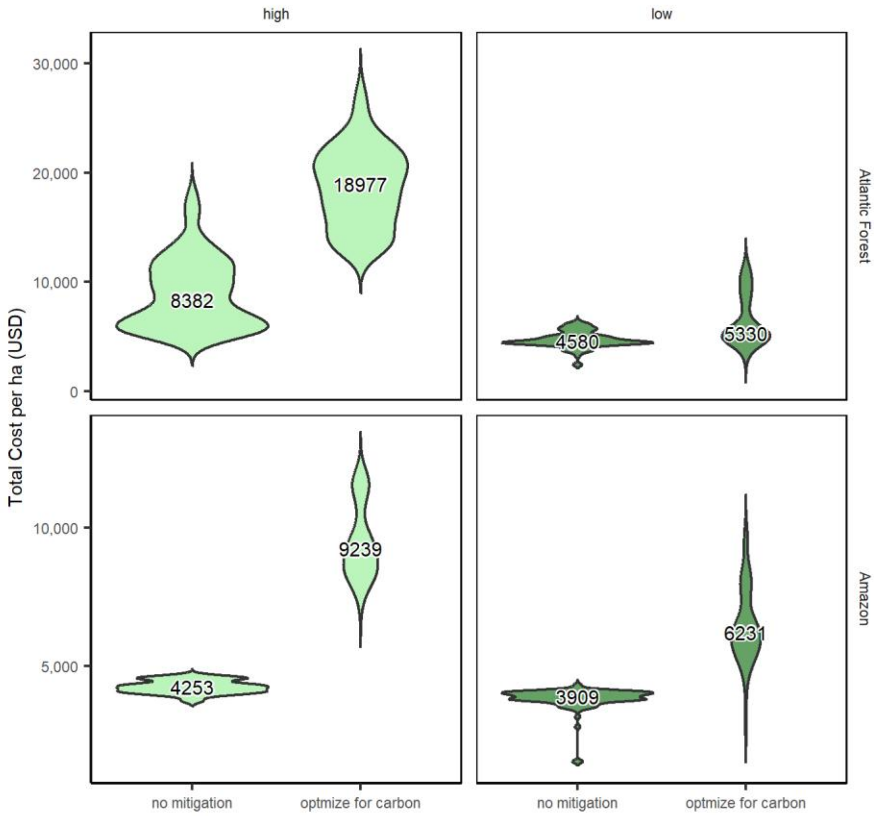


Extended Data Figure 4. Spatial heterogeneity in the forgone-production-to-carbon-lost ratio across domains for potential areas to select projects. (A) Distribution of forgone-production-to-carbon-gained ratios across national, Atlantic Forest biome, and Amazon biome scales. To improve visualization, the bottom 2.5% and top 2.5% of values were excluded from the density plots. Vertical lines represent the mean ratio values of selected low leakage (dark green) and high leakage (light green) projects in each biome (dotted lines for Amazon and continuous lines for the Atlantic Forest (B) Coefficient of variation (CV) of forgone-production-to-carbon-gained values at different domains considered for allocating leakage and mitigation: country, biome, and local.



Extended Data Figure 5. Impact of mitigation on total project costs across biomes and leakage scenarios. Violin plots show total project costs per hectare (in USD) under two mitigation approaches: no mitigation and carbon-optimized mitigation, where mitigation is prioritized in areas with high beef yield gaps and low carbon opportunity cost of forgone natural regeneratio. Panels represent combinations of biome (Atlantic Forest or Amazon) and leakage level (high or low). Medians are annotated, and violin widths reflect the distribution of cost values across projects. The values reflect the analysis at country domain.

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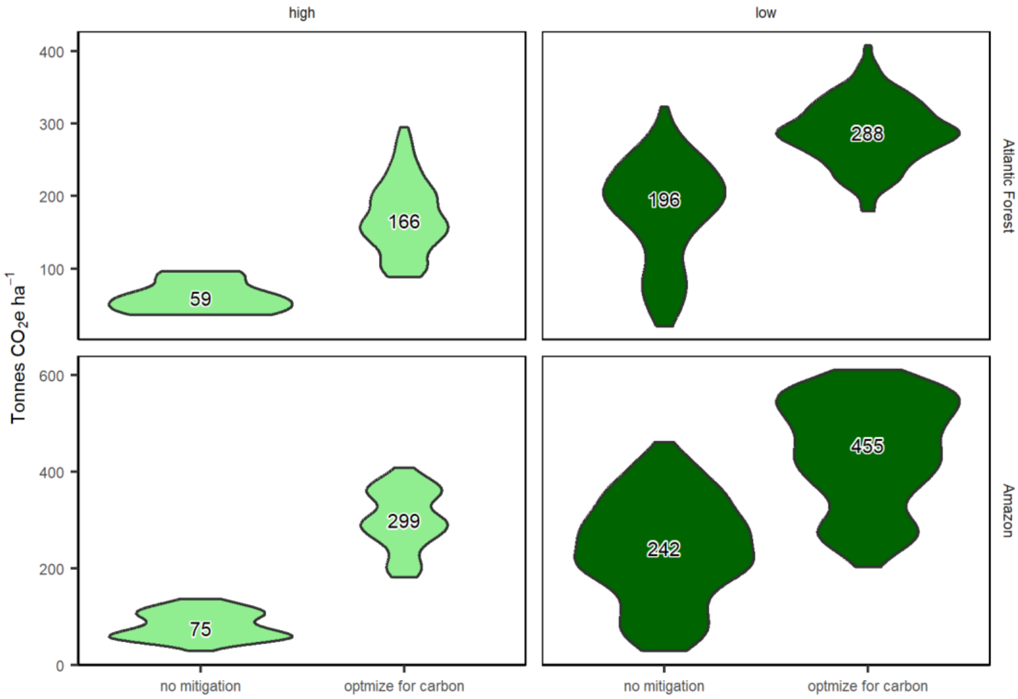
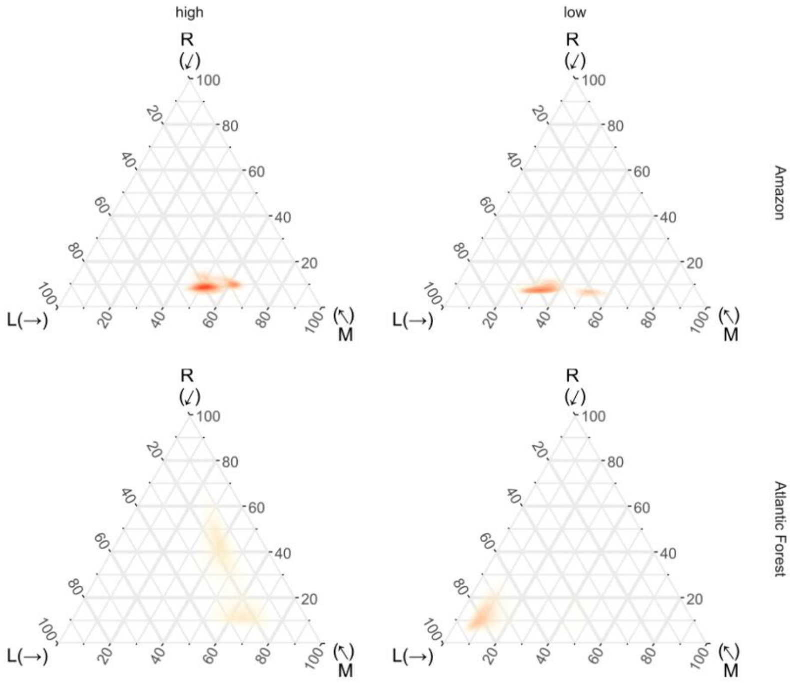
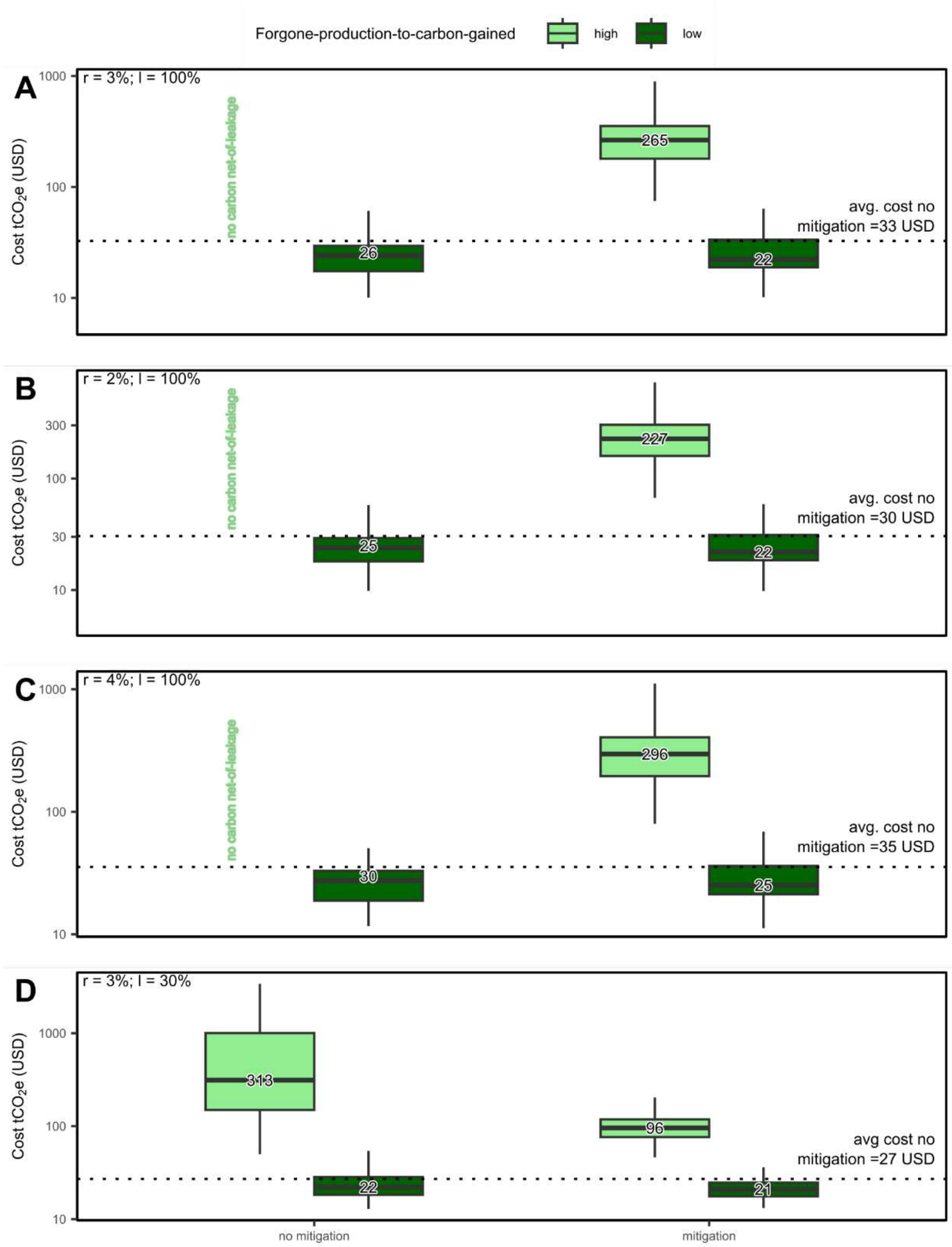


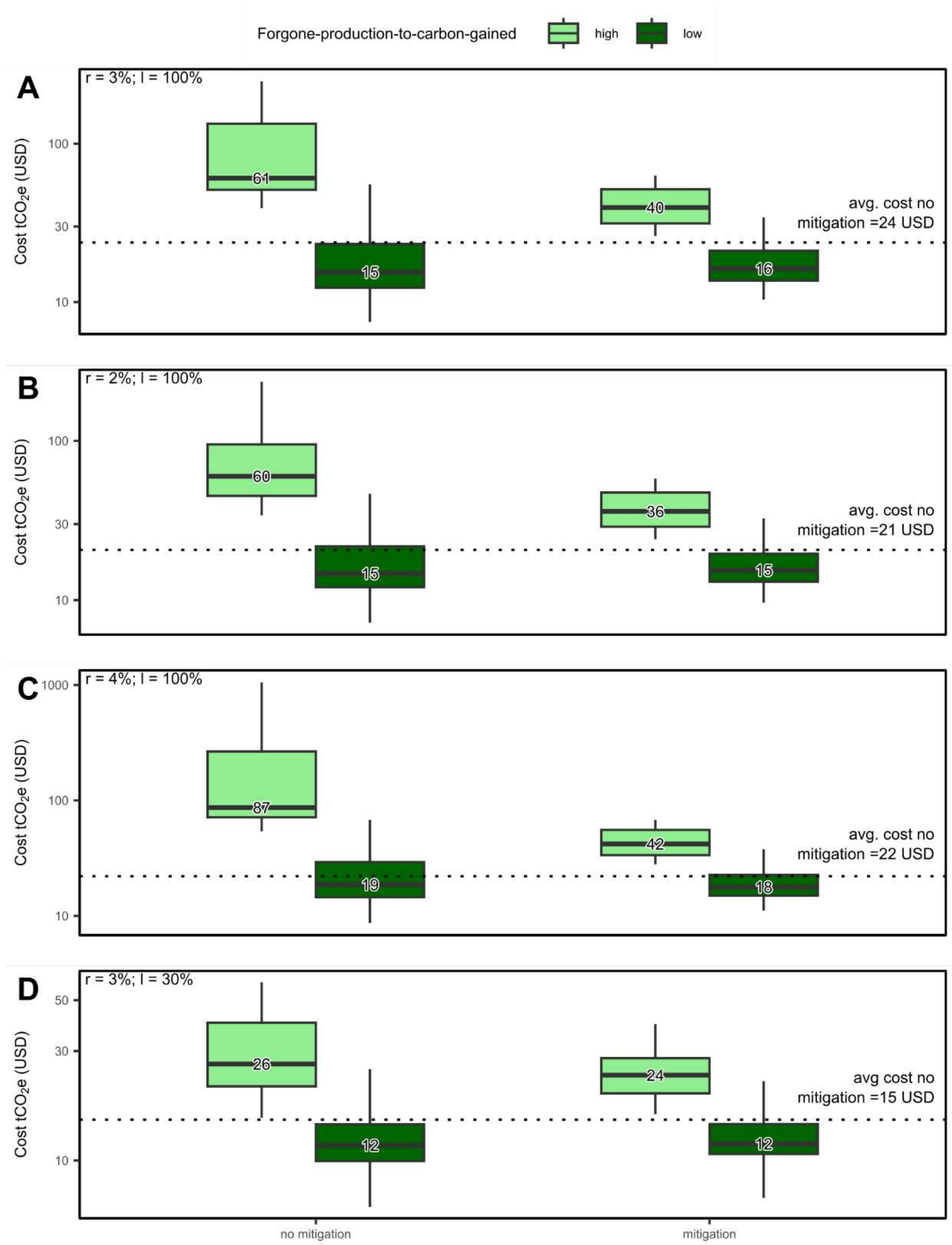
Extended Data Figure 6. Impact of mitigation strategy on net carbon balance across biomes and leakage scenarios. Violin plots show the distribution of net carbon removal ($tCO_2e\ ha^{-1}$) under two mitigation scenarios: no mitigation, and carbon-optimized mitigation, where mitigation is prioritized in areas with high beef yield displacement and low carbon potential. Panels are grouped by biome (Atlantic Forest or Amazon) and leakage level (high or low). The values reflect the analysis at country domain.



Extended Data Figure 7. Relative composition of restoration, land, and mitigation costs across projects. Ternary density plots show the % contribution of restoration (R), land (L), and mitigation (M) costs to total project expenditures across different biomes (Amazon and Atlantic Forest) and leakage levels (high and low). Each panel corresponds to one biome–leakage combination. Colour gradients from yellow to red reflect the density of projects with similar cost compositions, with reddish zones indicating the most frequent patterns.



Extended Data Figure 8. Sensitivity to leakage and discounting assumptions for projects in the Atlantic Forest. Carbon costs (USD tCO_2e^{-1}) of 200 restoration projects in the Atlantic Forest, shown for high-leakage (light green) and low-leakage (dark green) areas, with and without mitigation of displaced beef production. Boxplots show the distribution of costs across 100 high- and 100 low-leakage projects drawn from the upper (80^{th} %) and lower (20^{th} %) tails of the forgone-production-to-carbon-gained ratio distribution. The horizontal dotted line indicates the median cost of 100 randomly selected projects across the full forgone-production-to-carbon-gained ratio distribution (without mitigation). (A) Results for a 3 % discount rate (r = 3 %) and full leakage (l = 100 %), which represent our central analysis shown in the main text; (B–C) Sensitivity to discount rate (r = 2 % and r = 4 %, respectively); (D) Sensitivity to the assumed leakage rate, reducing l from 100 % to 30 % while keeping r = 3 %. The discount rate r is used in the calculation of the Social Cost of Carbon (SCC), which expresses the long-run carbon impacts of projects in present-day terms. Boxes show the interquartile range (IQR), whiskers extend to 1.5 × IQR, and numbers indicate median costs.



Extended Data Figure 9. Sensitivity to leakage and discounting assumptions for projects in the Amazon Forest. Carbon costs (USD t CO_2e^{-1}) of 200 restoration projects in the Amazon Forest, shown for high-leakage (light green) and low-leakage (dark green) areas, with and without mitigation of displaced beef production. Boxplots show the distribution of costs across 100 high- and 100 low-leakage projects drawn from the upper (80th percentile) and lower (20th percentile) tails of the forgone-production-to-carbon-gained ratio distribution. The horizontal dotted line indicates the median cost of 100 randomly selected projects across the full forgone-production-to-carbon-gained ratio distribution (without mitigation). (A) Results for a 3 % discount rate (r = 3 %) and full leakage (l = 100 %), which represent our central analysis shown in the main text; (B–C) Sensitivity to discount rate (r = 2 % and r = 4 %, respectively); (D) Sensitivity to the assumed leakage rate, reducing l from 100 % to 30 % while keeping r = 3 %. The discount rate r is used in the calculation of the Social Cost of Carbon (SCC), which expresses the long-run carbon impacts of projects in present-day terms. Boxes show the interquartile range (IQR), whiskers extend to 1.5 × IQR, and numbers indicate median costs.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

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