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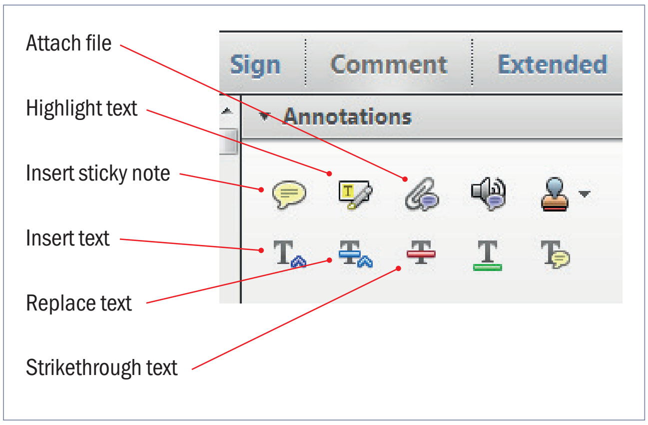

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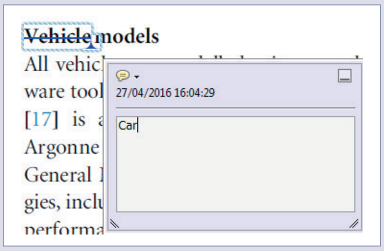

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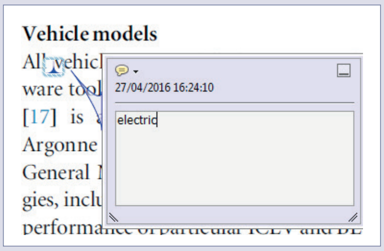

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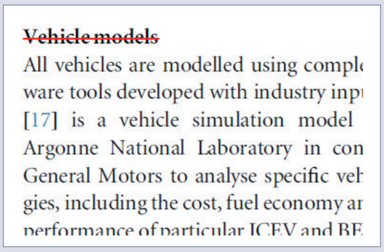

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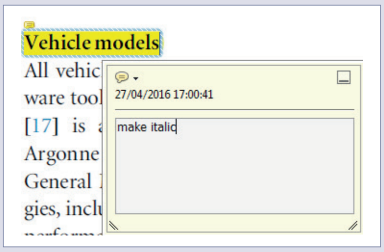

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LETTER

Enabling large-scale forest restoration in Minas Gerais state, Brazil

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Abstract

Large-scale forest restoration is a cornerstone of Brazil's new Forest Code and a key element in its National Determined Contribution (NDC) to emissions reduction. But the path to this target remains unclear due to a lack of information on its economics and implementation challenges. Here, we begin to fill this gap by developing a spatially-explicit model for Minas Gerais state that estimates the costs and benefits of native vegetation regeneration under different restoration approaches. Our results show that 36% of the Forest Code debt in Minas Gerais can be restored using only passive restoration, at a cost of US$ 175 ± 47 million. Adding low-cost assisted natural regeneration would increase that number to 75% (1.5 million ha) at a cost of US$ 776 ± 137 million over a 20 yr period. This would result in a potential sequestration of 284 $MtCO_2e$. However, including the intensive planting methods needed to restore the remaining 25% of highly degraded areas—to fully solve the Forest Code debt and result in a potential sequestration of 345 $MtCO_2e$—would more than double the costs to US$ 1.7 ± 0.3 billion. Our results emphasize the need to implement regional policies that take advantage of the natural regeneration potential as well as prioritize the restoration of areas key to ecosystem services.

1. Introduction

Brazil has recently made two significant overlapping commitments to reducing greenhouse gas emissions from land use change. In the first, part of its revised Forest Code (FC), although granting amnesty to some previous deforestation, has determined that an estimated 24 million ha of private lands must have native vegetation restored or offsetted to solve the FC debt past illegal deforestation (Soares-Filho *et al* 2016) . The second, presented as part of its Nationally Determined Contribution (NDC) to mitigate climate change, establishes a target of restoring or reforesting Q3 12 million hectares (Mha) by 2030 (Brazil 2015). If even partially implemented, these commitments will position Brazil as a world leader in forest restoration and reforestation. However, the challenges to meet these targets, the latter an area equivalent in size to England, are significant.

Chief amongst the implementation hurdles for the short term is a lack of economic information, including private and public costs, at a jurisdictional level. There are some local restoration estimates available that range from US$ 700 (IIS 2015) to more than US$ 4500 per hectare (Rodrigues *et al* 2009). But, since these costs may be prohibitive to most individual landowners, the identification of low cost opportunities is of paramount importance to effective implementation and adaptive management of climate change commitments and policy targets. To help overcome this hurdle, we quantify the natural regeneration potential across the state of Minas Gerais, Brazil, providing estimates of costs for large-scale restoration of native vegetation under different restoration methods. Our study also estimates environmental co-benefits in the form of priority areas relevant to ecosystem services, such as carbon sequestration, water, and biodiversity.

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1.1. Forest restoration methods

Reforestation and forest restoration have been widely recognized as an important action to mitigate climate change, enhance ecosystem services, improve forest habitat and thus biodiversity, and sustain the livelihoods of traditional populations (Wunscher *et al* 2008, Birch *et al* 2010, Wendland *et al* 2010, Nunes *et al* 2012, Locatelli *et al* 2015, Alexander *et al* 2016). As such, reforestation and native vegetation recovery has gained momentum within sustainable development and climate change mitigation strategies (SER 2004, Stanturf *et al* 2014, Nunez-Mir *et al* 2015). Indeed, forest ecosystems may regenerate to previous forest state once barriers to natural regeneration are removed (Holz and Placci 2005). Under suitable conditions, natural regeneration enables the self-organizing process of species colonization to initiate and create a recovery trajectory (Chazdon and Uriarte 2016). Furthermore, natural regeneration is a spontaneous long-term ecological process that occurs in stages, which can be managed or assisted to sustain local biodiversity and biotic interactions (Chazdon 2008).

Restoration can be classified into three groups: passive, intermediate and active. Passive restoration is based on a natural succession process, implying minimal human intervention (Holl and Aide 2011). This approach generally involves only the isolation of an area to allow for natural or unassisted native vegetation regeneration. Natural regeneration is affected by local resource availability, prior land use intensity, and dispersal of propagules (i.e. seeds and sprouts) (Rodrigues *et al* 2011, Pereira *et al* 2013, Chazdon 2014, Chazdon and Guariguata 2016). In this respect, abandoned pasturelands with high local resource availability near preserved forest remnants may be restored passively at a relatively low cost. The passive recovery process, however, can take place very slowly or be inhibited in degraded agroecosystems (Brancalion *et al* 2016).

As an intermediate step, there are techniques that expedite, rather than replace, natural successional processes by removing or reducing barriers to natural regeneration also referred to as Assisted Natural Regeneration (ANR) and may include, for example, the prevention and control of fire and invasive species (Corbin and Holl 2012, Evans *et al* 2015). Although ANR techniques may be less effective than replanting for enhancing floristic diversity at the initial stages, they offer significant cost advantages when compared to planting seedlings, which can make them a strategic choice for larger scale interventions (Shono *et al* 2007, Bechara *et al* 2016). Nevertheless, they seldom work if applied to deeply degraded sites or areas previously submitted to intense land use, which may have already surpassed an ecological threshold (Lamb *et al* 2005, Chazdon 2008, Chazdon 2013).

To deal with those areas, active restoration is required. Active restoration is generally carried out through interventionist practices, such as sowing and planting seedlings, in order to set a desired restoration trajectory (Rodrigues *et al* 2011). In some cases, plantations covering the entire area as well as techniques involving the planting small patches of trees (partial planting) to serve as focal areas for recovery have been recommended (Rodrigues *et al* 2011, Corbin and Holl 2012, Brancalion *et al* 2016). This increased silvicultural investment, while suitable to recover difficult situations, can affect the bottom line of the large-scale project. Common planting approaches utilized in the Brazilian Atlantic Forest, for example, range from US$ 3000 to over US$ 4500 per hectare (Rodrigues *et al* 2009, BNDES 2015). All of these methods can be combined to vary the level of intervention according to the site favorability, management goals, and available financial resources.

Indeed, the success or failure of a restoration project is a matter of finding the correct combination of restoration methods (Prach and Hobbs 2008, Clewell and McDonald 2009). In tropical areas, passive, intermediate and active methods have been proposed (IMAFLORA 2008, Cury and Carvalho 2011, TNC 2013), but the cost-effectiveness of these methods can vary greatly across sites depending on the availability of financial and human resources, degree of ecological degradation, and natural regeneration potential (Rodrigues *et al* 2011, Rezende *et al* 2015). In addition, economically profitable restoration models based on the exploitation of timber and non-timber forest products (Latawiec *et al* 2015, BIOFLORA 2015) from native species have been proposed but scientific and practical knowledge gaps remain (Silva 2013).

Despite its economic and environmental advantages, natural regeneration (either passive or assisted) is often neglected when reforestation and restoration policies are formulated. This is particularly important because, if done effectively, natural regeneration could free up limited financial resources to be applied in areas where more costly and intensive methods are needed (Chazdon and Guariguata 2016, Chazdon and Uriarte 2016).

1.2. Opportunities for large-scale restoration in Minas Gerais

Occupying approximately 7% of Brazil's territory, Minas Gerais is the second most populous state, the country's third largest economy and the second in agricultural value product (Cepea 2015). Nevertheless, the State still holds a vast natural capital. Native vegetation covers 17 Mha or 31% of the State (Soares-Filho *et al* 2013a), encompassing three Brazilian biomes, i.e. Cerrado, Atlantic Forest, and Caatinga. Although a significant agricultural producer, croplands shrunk in Minas Gerais by 13% between 1996 and 2006 (IBGE 2006) resulting in abandoned areas that now are under various stages of natural regeneration.

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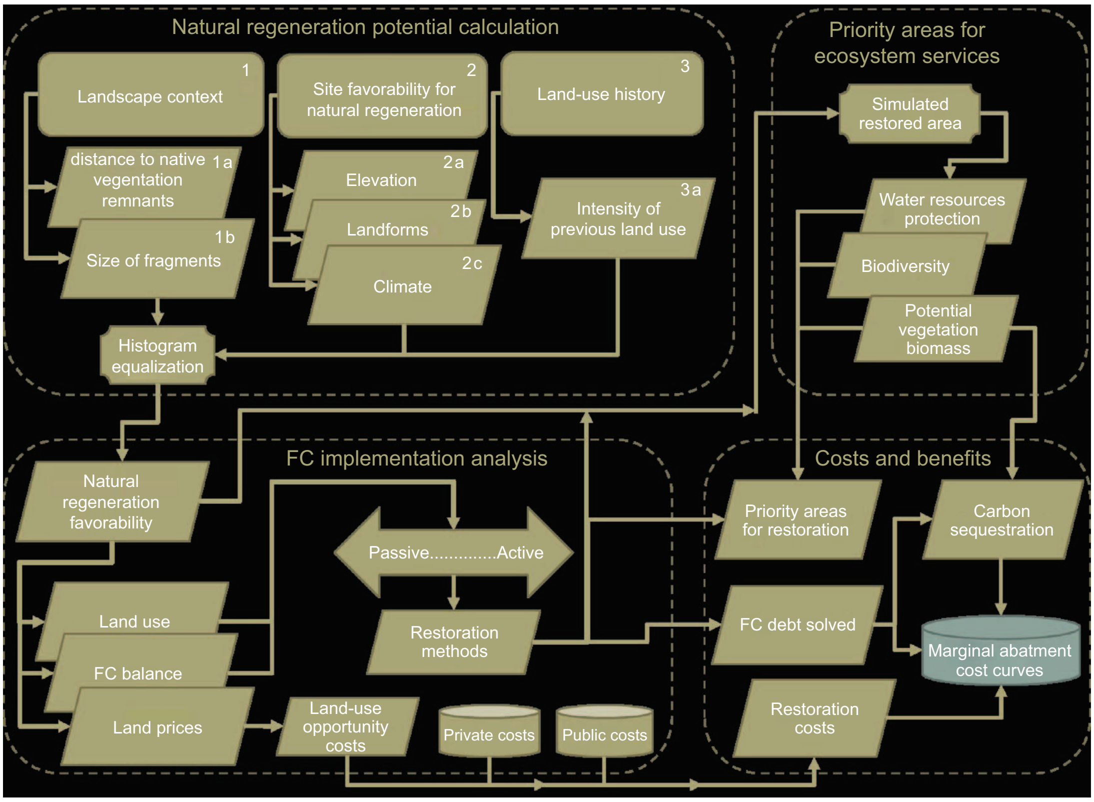

Figure 1. Modeling flowchart highlighting the main analysis modules (dashed lines) and their steps and inputs.

Minas Gerais needs one of largest restoration efforts in Brazil to comply with the Forest Code. Soares-Filho *et al* (2016) estimate there to be approximately 2 Mha of restoration needed in the State. These include an estimated 0.7 Mha in riparian buffer areas and 1.3 Mha of Legal Reserve a fraction of the landholding that must legally be maintained as native vegetation. Solving the FC debt in Minas Gerais is also pivotal for the success of the National Plan for Recovering Native Vegetation (PLANAVEG), which seeks to recover 12.5 Mha nationally in 20 yr as part of Brazils NDC policies.

2. Methods and material

2.1. General approach

We first began by using a suite of physiographic, climate and land use data to map the natural regeneration favorability. Favorability ranges can be interpreted as the local level of effort needed to foster restoration of the native vegetation through natural regeneration processes. The favorability map, together with maps of land use, land prices and the FC balance (levels of compliance), is used as inputs for a spatial optimization model that computes the natural regeneration potential for each micro-watershed at the 12th-order (ANA 2010). To pinpoint key ecological restoration zones, we superimposed potential restoration areas on maps of priority areas for enhancing ecosystem services, including carbon sequestration (Soares-Filho *et al* 2016), water resources protection (ANA 2013) and biodiversity (ZEEMG 2006). Spatial analyses were performed using Dinamica EGO freeware (Soares-Filho *et al* 2013b).

To comply with the FC, landowners must enroll in an Environmental Compliance Program (ECP), which regulates the use of different vegetation recovery methods ranging from passive restoration to a mix of native and exotic species plantations. We estimated the costs and benefits of a range of restoration methods, including passive restoration (PASRE), an intermediate method (ANR), and two active methods (PARPLAN and TOTPLAN) to solve the FC debt across the State. To calculate the total restoration costs, we include the private implementation and maintenance costs of each restoration method and the public government budget needed to monitor and verify the restoration actions. In addition to private and public costs, we estimated the land-use opportunity costs as they also represent a potential obstacle to the FC implementation (Stickler *et al* 2013). We then estimated the cost-effectiveness of each method by comparing the achieved levels of FC compliance with costs as well as the respective potential benefit of carbon sequestration. Results are presented as marginal abatement cost curves (figure 1).

2.2. Data

Our dataset comes from various sources (table S1 stacks.iop.org/ERL/00/000000/mmedia). The restoration implementation and maintenance costs were gathered

Table 1. Allocation of restoration methods and their main techniques based on the range of favorability for natural regeneration.

Restoration methods	Main techniques	Range of favorability for natural reg. (0–100)
Passive restoration	Site isolation from human disturbances	> 75
Assisted natural regeneration	Resprout protection and control of invasive species	50 to 75
Partial planting	Planting seedlings in islands (small patches)	25 to 50
Total planting	Planting seedlings covering the entire area	< 25

through interviews with technicians employed by the State environmental institutions (table S2). Other costs, such as the average freight price of seedlings, technical consultants (table S3), and government costs, were obtained from the State Rural Technical Assistance Agency and the State Forest Service (tables S4 and S5).

2.3. Quantifying the natural regeneration potential

Our analysis begins by mapping the landscape factors that have been identified to facilitate passive restoration. These include: 1) the landscape context, e.g. the surrounding land use matrix that may serve as an important source of propagules; 2) site favorability for natural regeneration, such as elevation, landform, and climate; and 3) land-use history. We translated these factors into the following spatial variables: (1a) distance to native vegetation remnants, (1b) size of fragments, (2a) elevation, (2b) landforms, (2c) climate, and (3a) intensity of previous land use (figure 1).

Over the landscape, sources of propagules in nearby forest fragments, especially in large forest remnants, favor natural regeneration (Martins *et al* 2014a). To estimate the local influence of the surrounding matrix, the model calculates the Euclidean distance to fragments of native vegetation and then normalizes these values into a standard range of favorability (1a). In addition, the model estimates the region of influence for each fragment of native vegetation based on its size, assigning all map cells to its nearest fragment (1b). We then multiply each favorability value by the size of the nearest fragment. Thus, areas equidistant from fragments of native vegetation may have different favorability of natural regeneration due to the size of the nearest fragment.

Regarding site favorability for natural regeneration, differences in elevation contribute to the dispersal of propagules as it favors the local seed availability in lower areas (2). Thus, to calculate the influence of elevation, we superimposed a hilltop map from Soares-Filho *et al* (2014) on the land use map in order to identify hilltops covered in native vegetation and then calculated the distance to these features (2a). Next, we identified landform forms that favor natural regeneration (2b). In general, concave forms and low-lying topographic areas (accumulation areas) contain higher soil moisture and nutrients that can contribute to the establishment of propagules. In this manner, we generated a slope map and calculated a cumulative flow map using an elevation map (NASA 2015) and a flow direction map. The resulting map indicates the cumulative flow received in a cell used to pinpoint accumulation areas. The model then categorizes ranges of favorability (see supplementary material—section 2.1). Similarly, areas with higher rainfall patterns positively influence the rate of natural regeneration (Holl and Aide 2011, Martins *et al* 2014a). We used a 30 yr annual average precipitation map for determining the local influence of climate (INMET 2015).

The rate of forest recovery is affected by the level of local degradation, as well as prior land use intensity through, for example, soil quality or seed dispersal (Holl and Aide 2011). To quantify the influence of land-use history we used the map of historical land use between 1940 and 2012 from Dias *et al* (2016) to estimate the previous intensity of land use (3 and 3a). The model generates probability (favorability) maps of natural regeneration potential for each factor by using a histogram equalization approach (Gonzalez and Woods 2008) (see supplementary material—section 2.2). These maps were then multiplied, and once again equalized, to generate an integrated favorability map (1–100) for the potential of natural regeneration. As a result, our fine spatial resolution approach (60 m × 60 m) enables the assessment of the integrated influence of key landscape features on the local natural regeneration potential as indicated by ecological restoration studies and technical manuals for Brazilian biomes (IMAFLORA 2008, Rodrigues *et al* 2011, Martins *et al* 2014a, Martins *et al* 2014b, BIOFLORA 2015).

2.4. Analyzing forest restoration under the FC implementation

The 60 m × 60 m spatial resolution land cover map (figure S1) used as input for simulating restoration areas comes from Soares-Filho *et al* (2014). We overlaid this map with a land use map (Soares-Filho *et al* 2016) and the FC balance map (Soares-Filho *et al* 2014) to identify pasturelands below the FC compliance. The model is constrained to allocate restoration on pasturelands only, due to their low land prices in comparison with croplands (Soares-Filho *et al* 2016). The model also excludes future areas of agricultural expansion, projected for 2030 by the OTIMIZAGRO model (Soares-Filho *et al* 2016), from consideration. The model then allocates the amount of restoration required by the FC within a micro-watershed (figure S2) selecting the appropriate restoration method according to the level of natural regeneration favorability calculated previously (table 1). The set

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Table 2. Restoration methods and private costs of implementation and maintenance.

Restoration methods	Private costs of implementation and maintenance per hectare (US$)
Passive restoration	639 ± 172
Assisted natural regeneration	1230 ± 172
Partial planting	2568 ± 487
Total planting	3631 ± 941

of methods selected constitutes an increasing gradient of effort to conduct a restoration project based on the range of natural regeneration potential. The practices and techniques included per restoration method, as well as average costs and standard deviations are listed in the supplementary material (table S2).

2.5. Calculating costs and benefits

Private costs were estimated per hectare for the four restoration methods. We included two years of maintenance costs beyond the initial implementation costs, resulting in a three-year disbursement schedule (table 2). We assumed that all restoration projects need specialized technical support at a cost of 2% of the total value (table S3). Standard deviations are calculated from the price ranges based on differences in fencing options and seedling spacing per hectare. The cost of fencing also depends on the shape and size of a restoration parcel. We assume that the legal reserve restoration areas are approximately square and fenced on three sides, on average, and the riparian restoration areas are linear shape and are fenced on two sides, on average. The cost of fencing the legal reserve varies from US$ 811 per ha for parcels of between 0 and 20 ha, and US$ 247 per ha for parcels of more than 20 ha, and increases linearly with the length of the riparian recovery.

A discount rate of 8% was used in calculating Net Present Values (NPV) (World Bank 2010) over a 20 yr period required in the ECP. We project total private costs under the assumption that 10% of the FC compliance targets will be met every 2 yr, as required by the law. To account for verification and monitoring costs, which must be carried out by the state government, we included an additional budget for the public effort. To estimate the public costs, we added preliminary government costs of land use registry validation and onsite verification (table S4) as well as administrative costs obtained from the state 'Bolsa Verde' Program (table S5). The costs are also discounted annually. Brazilian currency was converted to US$ using the mean exchange rate of 2015 (1 US$ = 3.33 R$). The opportunity costs were calculated as the difference between pastureland prices and forested land prices (figures S3 and S4). To compose the global budget, we sum the private and public costs, and then add the opportunity costs of compliance.

2.6. Prioritizing areas to enhance ecosystem services

We estimated the potential benefits of forest restoration in terms of FC compliance and carbon sequestration. To do so, the model deducts the areas appropriate for each restoration method from the total area requiring restoration, thus calculating the potential percentage of compliance attained by applying each one of the four methods. To estimate potential carbon sequestration, we laid a map of potential vegetation biomass from Soares-Filho *et al* (2016) over the areas restored under each method to quantify the carbon sequestration over a 20 yr period (figure S5). We assumed a recovery threshold of 44% of the potential biomass for the 20 yr of restoration period and a biomass carbon content of 50% (MCTI 2015).

We superimposed the map of simulated restored areas (see supplementary material—section 2.3) on the map of potential vegetation biomass (figure S5), the map of areas under water stress (figure S6), and the maps of priority areas for fauna and flora protection (figures S7 and S8) to pinpoint priority restoration areas for enhancing ecosystem services.

3. Results

We estimate that approximately 30% (8 Mha) of the total pasturelands in Minas Gerais holds medium to high natural regeneration potential. Of this total, 5.7 Mha are located in the Atlantic Forest, 2.2 Mha occur in the Cerrado, and 0.1 Mha in the Caatinga (figure 2). The intersection of these areas with the map of the FC balance shows that roughly 36% (0.7 Mha) of the FC debt could be solved using PASRE only and 75% (1.5 Mha) by adding ANR (figure 3). These areas would represent 6% and 12% of the Brazils total NDC restoration target. The remaining 25% of the FC requirement in Minas Gerais (2% of Brazil's total) is located in regions with low natural regeneration potential and thus need the employment of more costly methods such as PARPLAN and TOTPLAN (figure 4).

Private costs to meet the PASRE and ANR targets would amount to US$ 175 ± 47 and US$ 715 ± 135 million, respectively (table 3). Although covering a small fraction of the FC debt, the costs of PARPLAN and TOTPLAN represent an additional 55% to the total private costs. The total private cost, for all four methods, to solve the FC debt in Minas Gerais is estimated at approximately US$ 1.6 ± 0.3 billion. Our estimates of public costs for implementing the ECP are US$ 90 million, making the sum of private and public cost approximately US$ 1.7 ± 0.3 billion. It is possible, however, that in the absence of law enforcement land-use opportunity costs present a potentially greater barrier to compliance. Our results suggest that when the opportunity costs of compliance are included the total costs of compliance shoot up to US$ 4.8 ± 1.5 billion.

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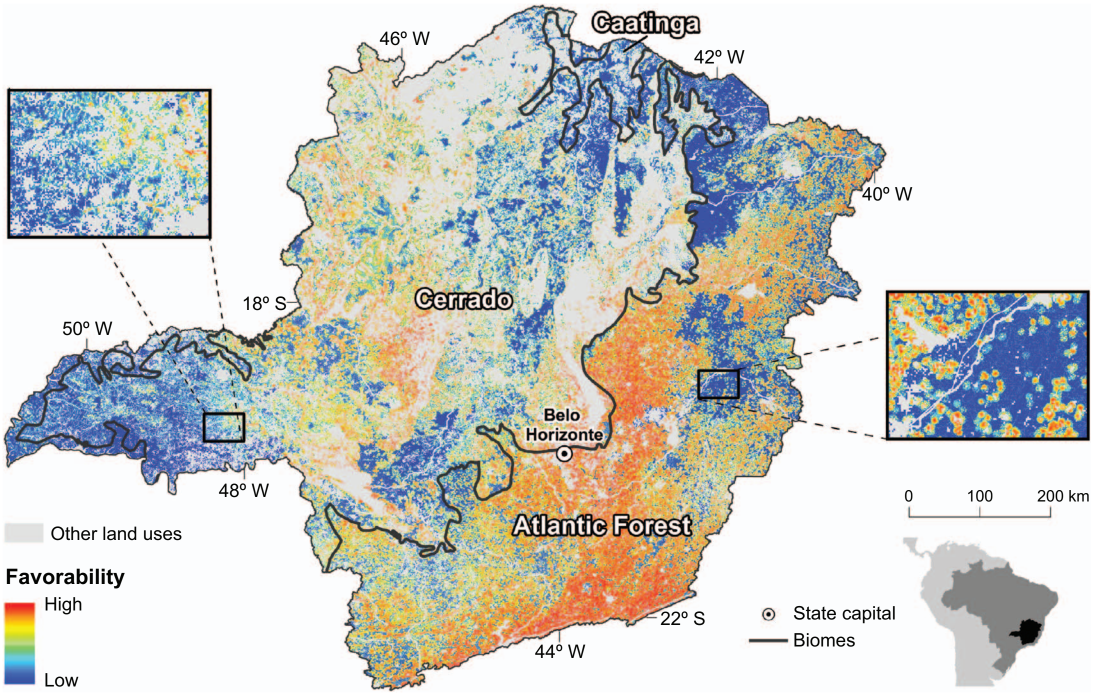

Figure 2. Favorability for natural regeneration on pasturelands of Minas Gerais.

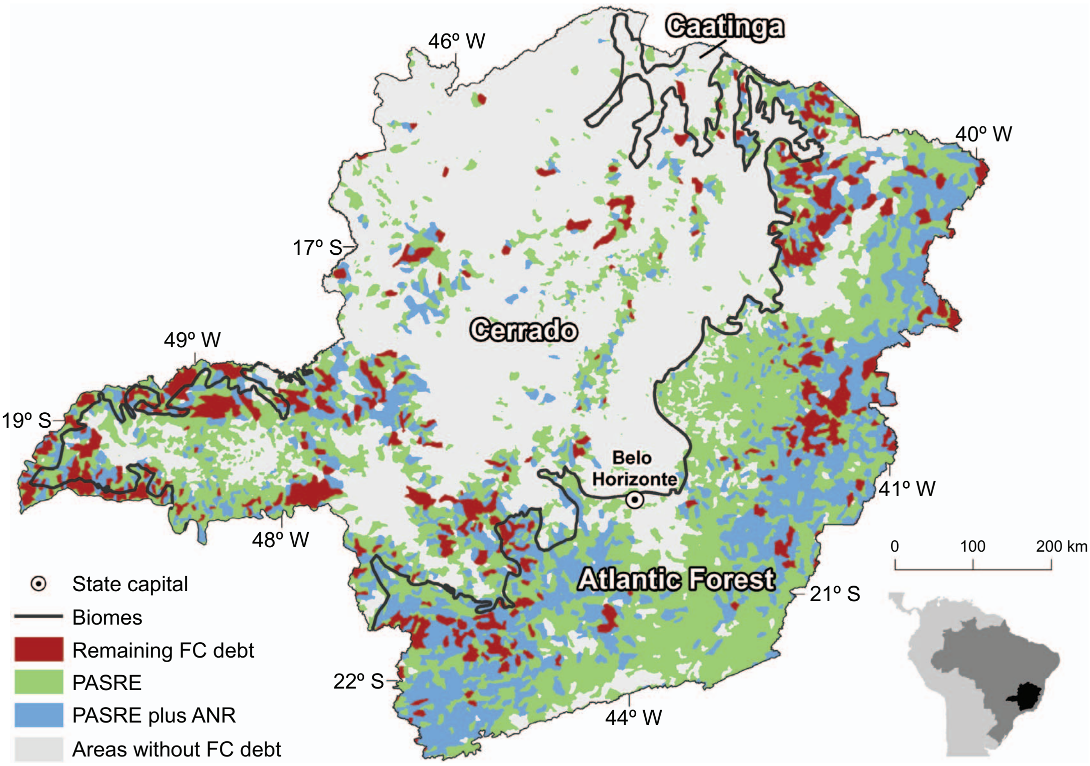

Figure 3. Solving the FC debt by employing PASRE and ANR. The remaining FC debt would require PARPLAN and TOTPLAN methods.

Fully solving the FC debt in Minas Gerais would sequester 345 ± 86 $MtCO_2e$, but the cost per ton varies greatly. A price of US$ 1.1 per tCO_2e would cover the private costs where only PASRE is needed over a 20 yr period—at this price, the mean carbon sequestration per hectare (220 ± 85 $tCO_2e\ ha^{-1}$) would suffice to pay the marginal costs of fencing (240 US$ ha^{-1}). In contrast, prices would need to increase to between US$ 8 or 10 per tCO_2e to cover the costs of PARPLAN and TOTPLAN investments (figure 5).

Finally, in the terms of ecosystem services, the most relevant areas for targeting large-scale restoration

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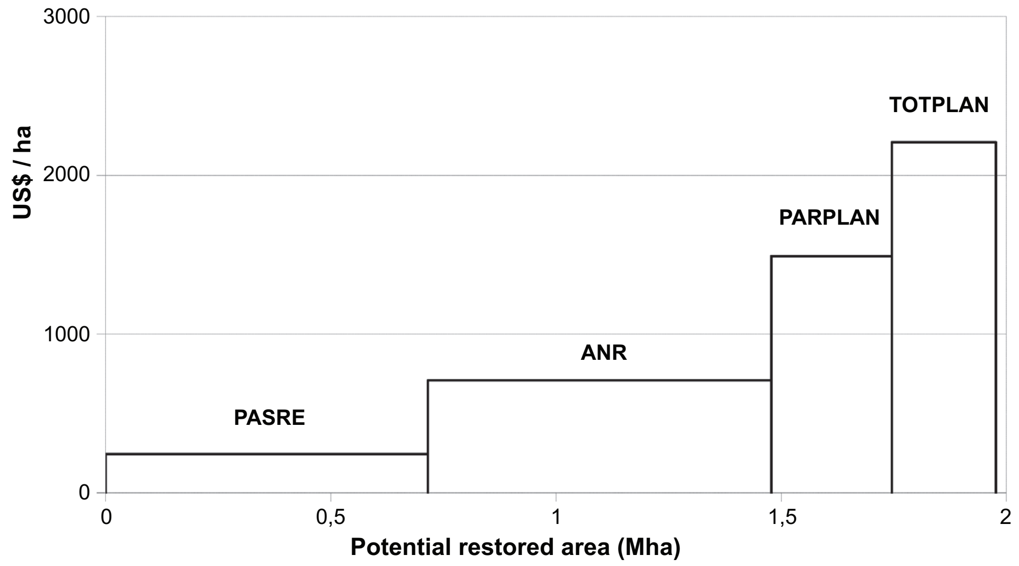

Figure 4. Marginal abatement cost curve for restoration of native vegetation.

Table 3. Private costs of restoration, public costs, and opportunity costs of compliance in NPV.

Restoration method	Potentially restored area (thousand ha)	Private costs (US$ Million)	Public costs (US$ Million)	Opportunity costs (US$ thousand/ha)
Passive restoration	715	175 ± 47	30 ± 1.0	1.4 ± 0.4
Assisted natural regeneration	763	540 ± 88	31 ± 1.0	1.6 ± 0.6
Partial planting	268	398 ± 75	11 ± 0.3	1.8 ± 0.7
Total planting	230	508 ± 126	9 ± 0.3	2.0 ± 0.9

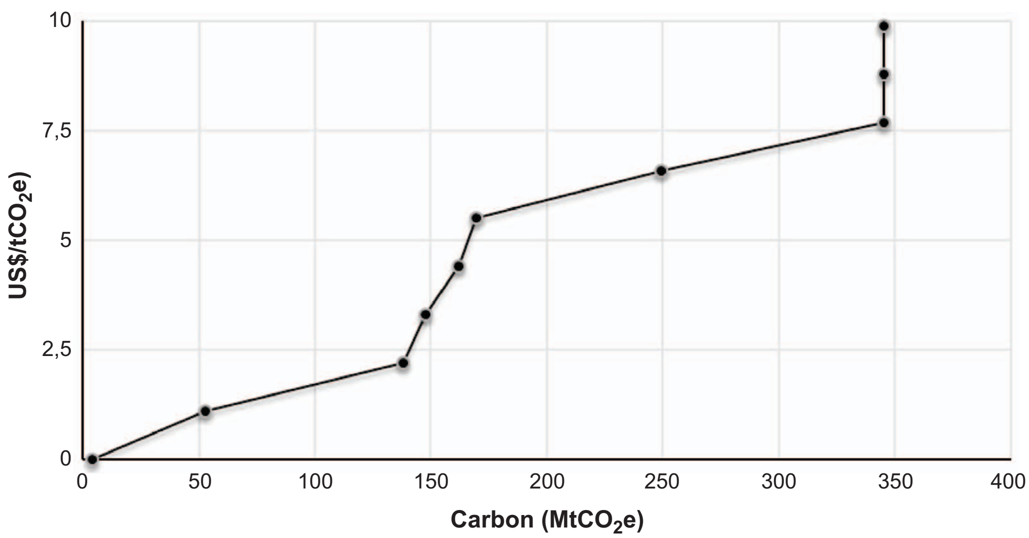

Figure 5. Marginal abatement cost curve for carbon sequestration.

are located in the south of the state along the Mantiqueira ridge as well as along the Espinhaço ridge in central and north of the state (figure 6). Indeed, a wider restoration program to meet the more ambitious targets of 'The Atlantic Forest Restoration Pact' (Rodrigues *et al* 2011, Pinto *et al* 2014) could be promoted through payments for ecosystem services (PES), such as the State's Program 'Bolsa Verde' (IEF 2014). These payments should cover the land-use investments needed for fostering passive restoration as well as land-use opportunity costs of properties above compliance. Such an initiative would need US$ 416 ± 116 million to target 250 000 hectares over a 20 yr period. Our estimates indicate that a carbon price of US$ 7.5 per tCO_2e would suffice to cover this budget resulting in a potential sequestration of 55 $MtCO_2e$.

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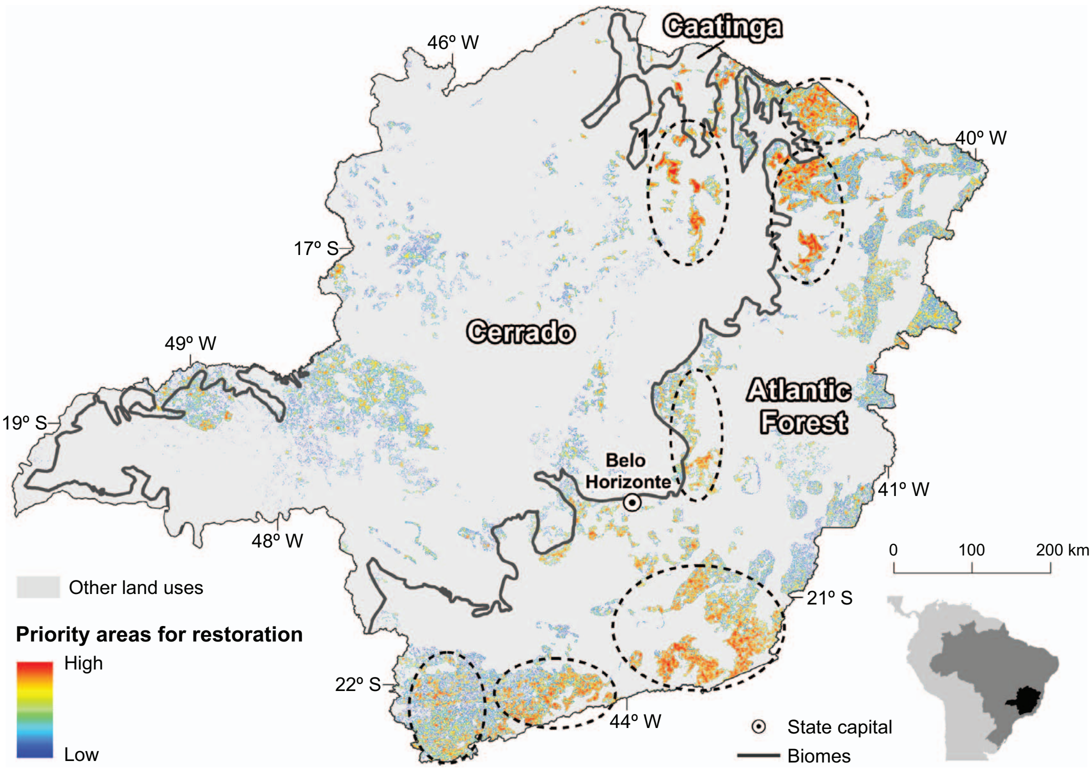

Figure 6. Priority areas of the FC debt in Minas Gerais for large-scale restoration projects aimed to enhance ecosystem services, including carbon sequestration, water resources protection, and biodiversity conservation. Ellipses depict major areas.

4. Discussion and conclusion

The model developed in this study employed a combination of methods for mapping the natural regeneration potential in Minas Gerais, which represents a key issue for the implementation of Brazil's FC. While forest ecosystem models involve complex processes to simulate the vegetation structure and dynamics (Hurtt *et al* 2016), our fine spatial resolution approach enables to model the effect of policy actions on the recovery of native vegetation. As a result, our study confirms the findings of Martins *et al* (2014a) that areas with high to medium potential for passive restoration can be found at the landscape level. The vast area to be restored and its associated cost variation will require different degrees of intervention that combine passive, intermediate and active restoration methods. Planting seedlings, the most widely, and often costly, restoration approach, may not be feasible to achieve the restoration needs in Minas Gerais. Our results reinforce the role of natural regeneration in significantly reducing the cost of large-scale restoration (Chazdon and Guariguata 2016). Policies aimed at FC success—a total of 2 Mha restored in Minas Gerais—under the NDC/PLANAVEG should therefore prioritize areas with high natural regeneration potential, which cover 1.5 Mha, across the State.

There is, therefore, a need to develop an appropriate legal framework within the ECP that recognizes the possibility of application of a wide range of restoration methods according to the site suitability, thereby avoiding 'one size fits all' solutions (Durigan *et al* 2010, Aronson *et al* 2011).

Although there are opportunities for large-scale forest restoration via low-cost approaches, it is essential to acknowledge the many obstacles ahead. The first barriers include challenges related to large-scale governance and the lack of long-term studies for assessing costs and ecological benefits of restoration (Metzger and Brancalion 2013, Wheeler *et al* 2016). Furthermore, understanding how much landowners are willing to internalize the substantial opportunity cost related to forest restoration is key. Theory suggests that individual farmers would restore their forest if the cost of remaining non-compliant is greater than the land-use opportunity cost. However, practical approaches by non-profit groups, such as Aliança da Terra (www.aliancadaterra.org), have demonstrated significant conservation investments by landowners without direct compensation.

As the choice of the most appropriate restoration method depends on a local diagnosis (Reis *et al* 2003, Rodrigues *et al* 2009, Rodrigues *et al* 2011), the four restoration methods proposed in this study should not be seen as packages ready for restoration projects but rather a set of restoration approaches to be customized and even combined according to local conditions and landscape contexts. It is also important to recognize the caveats of the modelling approach. By defining and spatializing the influence of variables related to natural regeneration potential, our results might underestimate the local impact of the historical land-use and the ecosystem resilience in some areas. Therefore, local diagnosis is still needed to accurately estimate the site potential for local regeneration.

In sum, our results provide policy makers with the geographic opportunities and the magnitude of the private and public efforts required to foster large-scale forest restoration in Minas Gerais. Still, enabling large-scale forest restoration in Minas Gerais also relies on advancing the science and practice of ecological restoration together with effective regional policies aimed at the FC implementation, especially, the Environmental Compliance Program. And if we want to promote restoration beyond the FC compliance, these policies should contemplate PES programs, such as the State's program Bolsa Verde. Regarding the latter, the extended market of forest certificates, named XCRA (Soares-Filho *et al* 2016), potentially offers a unique opportunity to disseminate PES programs Q4 across Brazil.

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