Environmental Research Letters

LETTER

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

Felipe S M Nunes[1,5], Britaldo S Soares-Filho[2], Raoni Rajão[3] and Frank Merry[4]

[1] Fundação Estadual do Meio Ambiente—FEAM, Gerência de Energia e Mudanças Climáticas—GEMUC. Belo Horizonte, Minas Gerais, CEP 31630-900, Brazil
[2] Universidade Federal de Minas Gerais—UFMG, Centro de Sensoriamento Remoto—CSR. Av. Antônio Carlos, 6627, Belo Horizonte, MG, CEP 31270-900, Brazil
[3] Universidade Federal de Minas Gerais—UFMG, Laboratório de Gestão de Serviços Ambientais—LAGESA, Av. Antônio Carlos, 6627 Pampulha, Belo Horizonte, MG, Brazil
[4] Conservation Strategy Fund, Washington DC, United States of America
[5] Author to whom any correspondence should be addressed.

E-mail: felipe.nunes@meioambiente.mg.gov.br

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% (0.7 million ha) 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 hectares (Mha) 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 12 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.

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, Bechara *et al* 2016, 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,
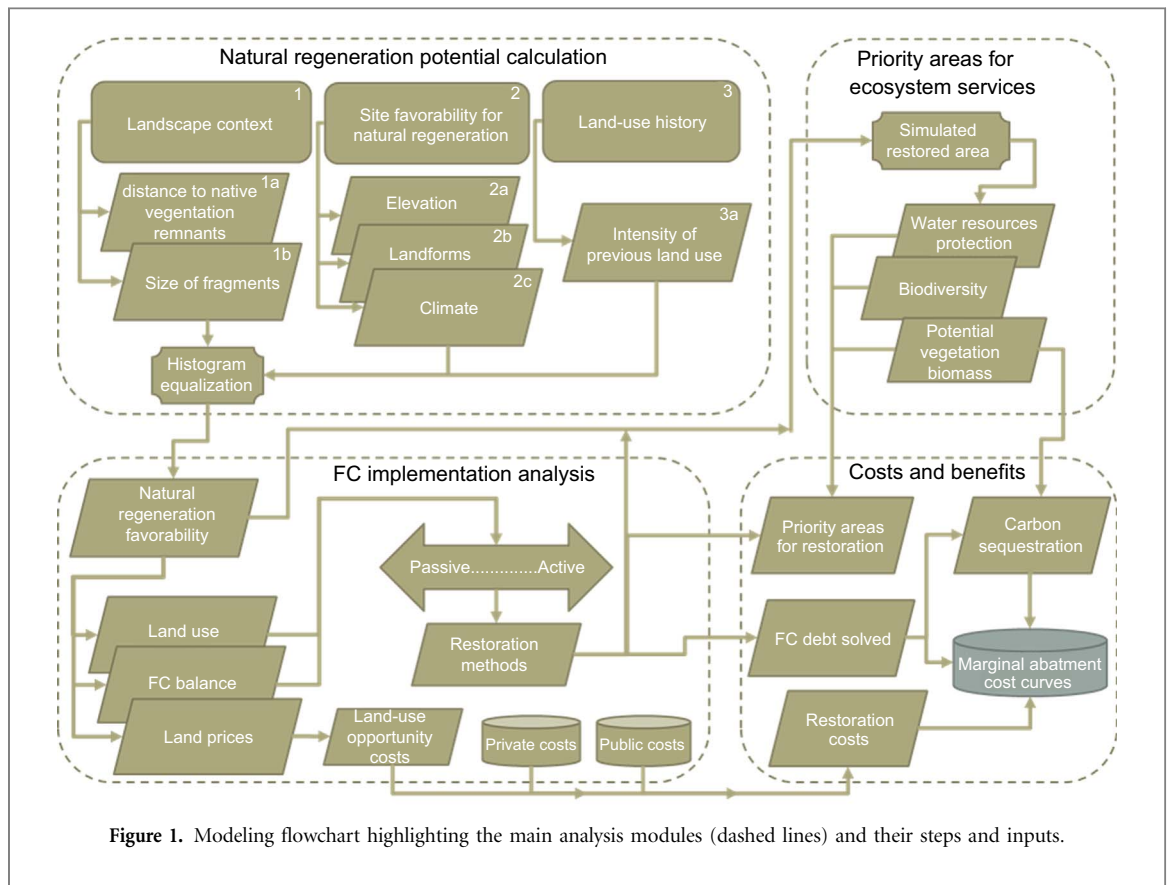
Figure 1. Modeling flowchart highlighting the main analysis modules (dashed lines) and their steps and inputs.

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.

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 Brazil's 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 included 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 available at stacks.iop.org/ERL/12/044022/mmedia). The restoration implementation and maintenance costs were gathered 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 multiplied 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) (Martins *et al* 2014a). 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 (Martins *et al* 2014a). 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 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 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

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

(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 assumed 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 projected 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 summed the private and public costs, and then added 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
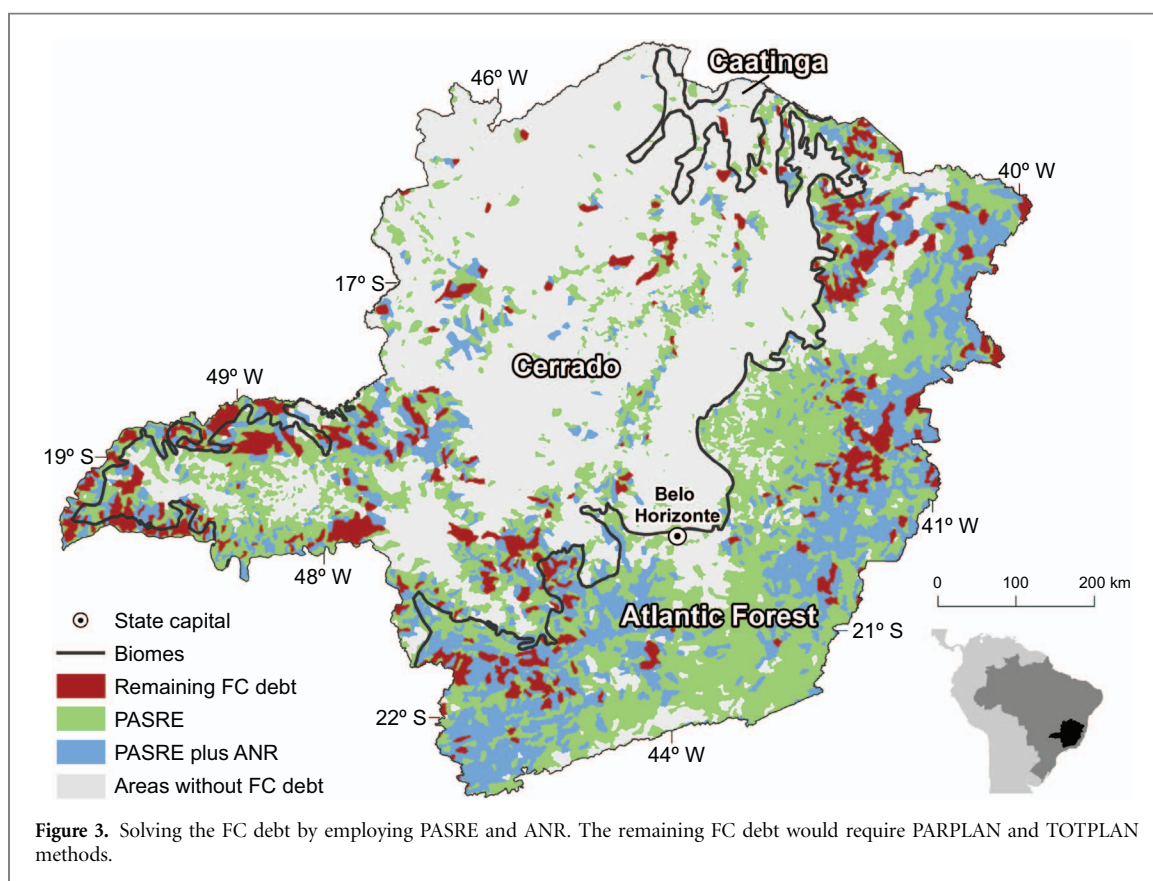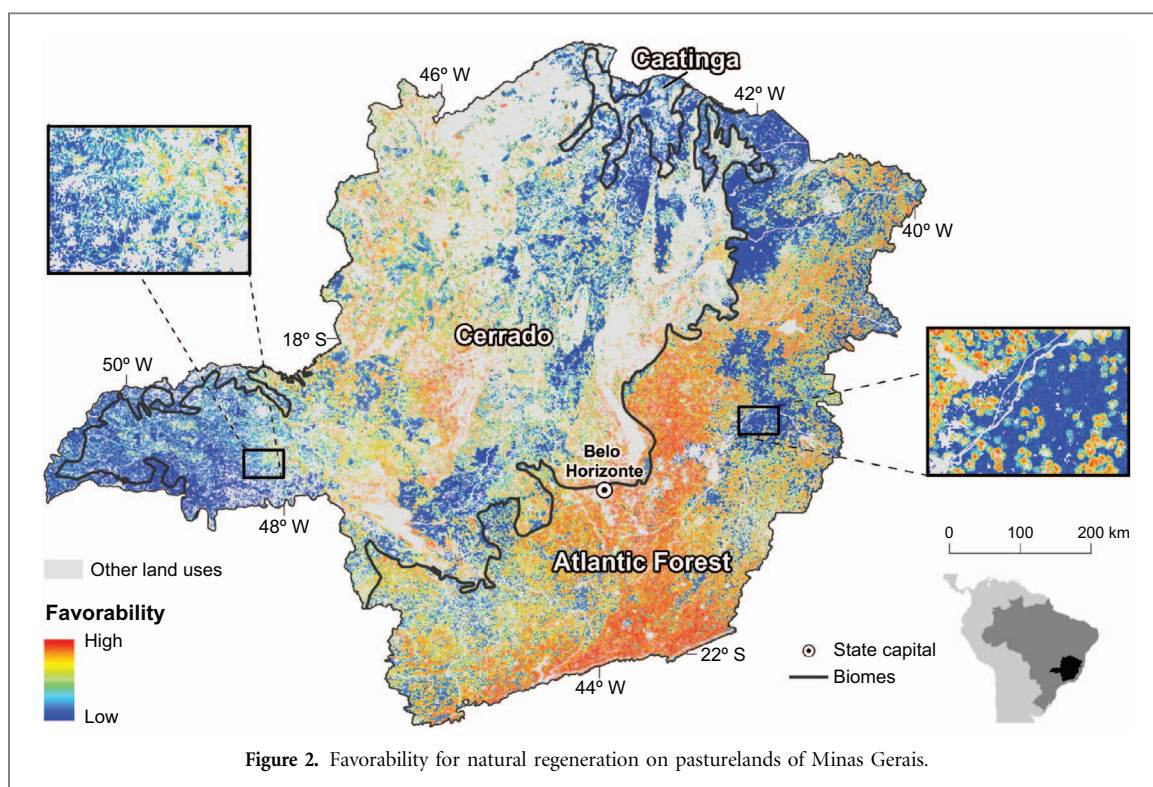
sequestration. To do so, the model deducts the areas appropriate for each restoration method from the total area requiring restoration, thus calculating the potential percentage of compliance attained by applying each one of the four methods. To estimate potential carbon sequestration, we laid a map 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 Brazil's 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,

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.

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.

Fully solving the FC debt in Minas Gerais would sequester 345 ± 86 MtCO$_2$e, but the cost per ton varies greatly. A price of US$ 1.1 per tCO$_2$e 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$_2$e ha^{-1}) would suffice to pay
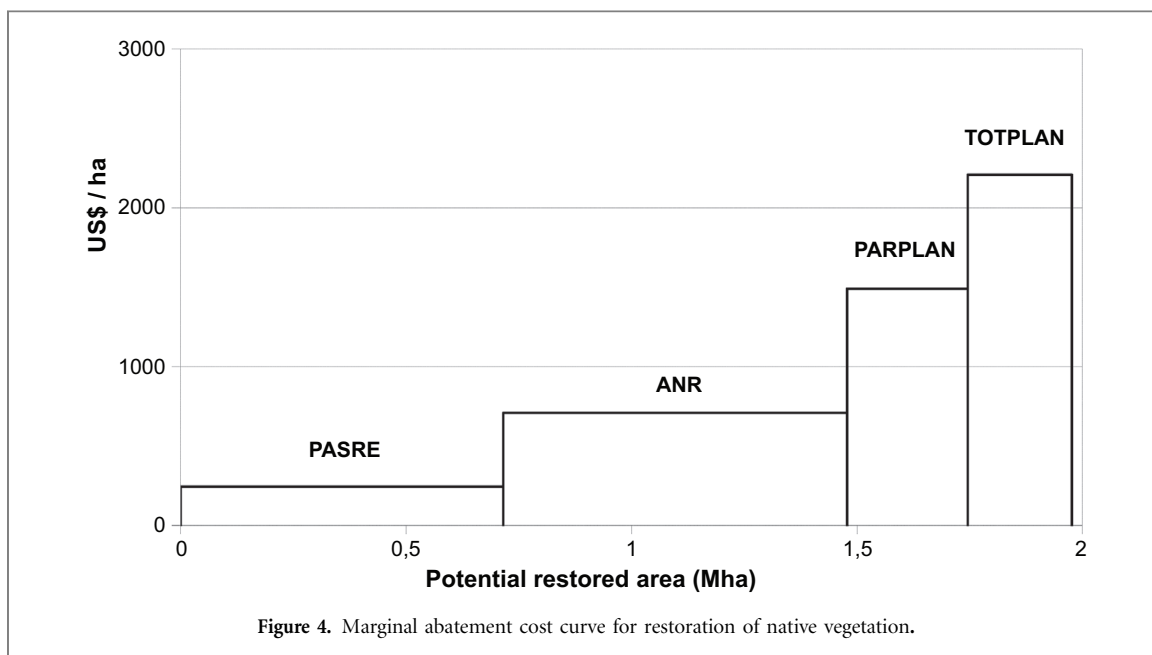
Figure 4. Marginal abatement cost curve for restoration of native vegetation.

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

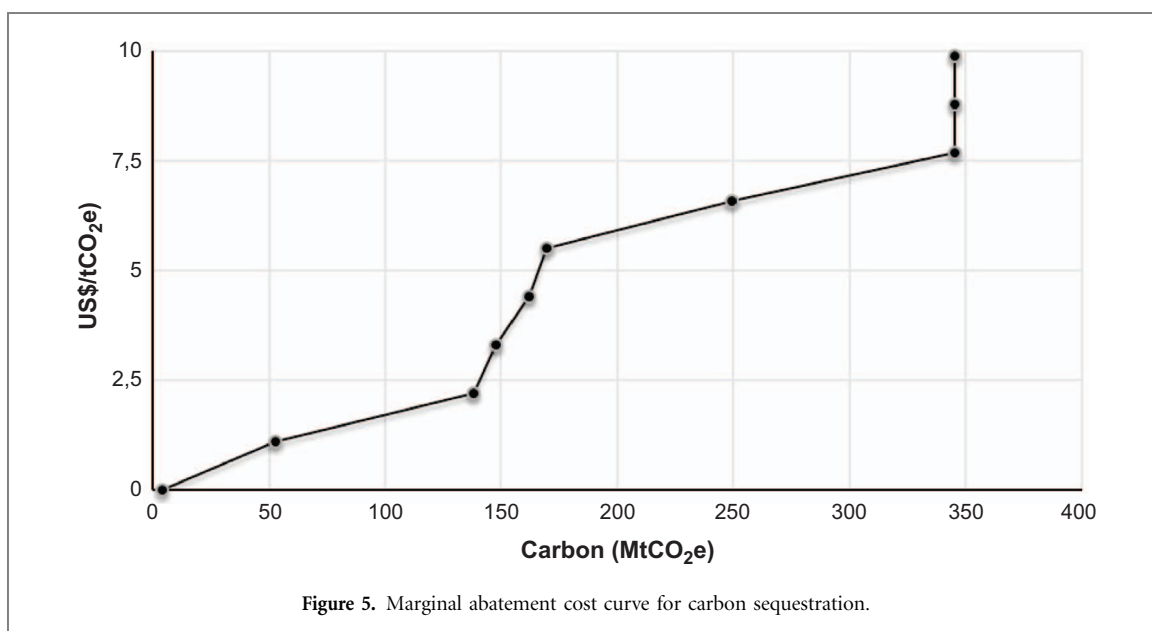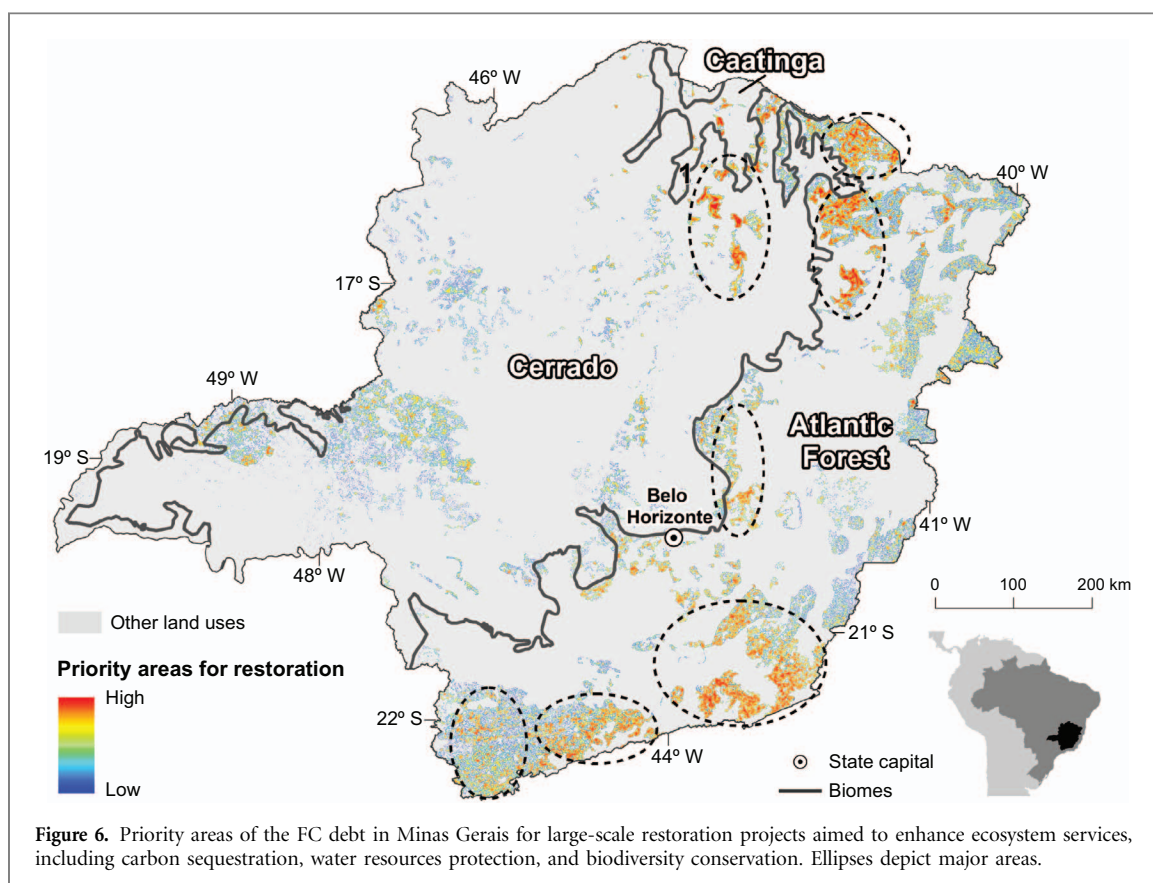| Restoration method	Potentially restored area (thousand ha)	Private costs (US$ Million)	Public costs (US$ Million)	Opportunity costs (US$ thousand/ha)
Passive restoration	715	175 ± 47	30 ± 1.0	1.4 ± 0.4
Assisted natural regeneration	763	540 ± 88	31 ± 1.0	1.6 ± 0.6
Partial planting	268	398 ± 75	11 ± 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.

the marginal costs of fencing (240 US$ ha^{-1}). In contrast, prices would need to increase to between US$ 8 or 10 per tCO$_2$e 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 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

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.

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 $MtCO_2e$.

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 across Brazil.

Acknowledgments

References

Alexander S, Aronson J, Whaley O and Lamb D 2016 The relationship between ecological restoration and the ecosystem services concept *Ecol. Soc.* **21** 34

Agencia Nacional de Aguas ANA 2010 Portal de Metadados (http://metadados.ana.gov.br/geonetwork/srv/pt/main.home) (Acessed: December 2015)

Agencia Nacional de Aguas ANA 2013 Conjuntura dos Recursos Hídricos no Brasil 2013 (http://arquivos.ana.gov.br/institucional/spr/conjuntura/webSite_relatorioConjuntura/projeto/index.html) (Acessed: December 2015)

Aronson J *et al* 2011 What role should government regulation play in ecological restoration ongoing debate in São Paulo State *Brazil Restor. Ecol.* **19** 695

Bechara F C, Dickens S J, Farrer E C, Larios L, Spotswood E N, Mariotte P and Suding K N 2016 Neotropical rainforest restoration: comparing passive, plantation and nucleation approaches *Biodivers. Conserv.* **25** 2021

BIOFLORA Tecnologia da Restauração 2015 Manual De Restauração Ecológica Técnicos e Produtores Rurais No Extremo Sul Da Bahia (www.viveirobioflora.com.br/files/file_texto_123.pdf) (Accessed: December 2015)

Birch J C, Newton A C, Aquino C A, Cantarello E, Echeverría C, Kitzberger T, Schiappacasse I and Garavito N T 2010 Cost-effectiveness of dryland forest restoration evaluated by spatial analysis of ecosystem services *Proc. Natl Acad. Sci.* **50** 21925–30

BNDES 2015 Iniciativa Mata Atlântica (https://web.bndes.gov.br/bib/jspui/handle/1408/4421) (Accessed: December 2015)

Brancalion P D S, Gaudare U, Mangueira J, Lamonato F, Farah F and Rodrigues R R 2016 Balancing economic costs and ecological outcomes of passive and active restoration in agricultural landscapes: the case of Brazil *Biotropica* **48** 856–67

Brazil 2015 Intended nationally determined contribution towards achieving the objective of the United Nations framework convention on climatechange 2015 (www4.unfccc.int/submissions/indc/) (Accessed: December 2015)

Centro De Estudos Avançados Em Economia Aplicada Cepea 2015 GDP Agribusiness—Outlook (www.fao.org/3/a-i4738e.pdf) (Accessed: December 2015)

Chazdon R L 2008 Beyond deforestation: restoring forests and ecosystem services on degraded lands *Science* **320** 1458–60

Chazdon R L 2013 Regenerating tropical forest ecosystem *Encyclopedia of Biodiversity* vol **7** 2nd edn, ed S Levin (Waltham, MA: Academic) pp 277–86

Chazdon R L 2014 *Second Growth: The Promise of Tropical Forest Regeneration in an Age of Deforestation* (Chicago: University of Chicago Press) p 485

Chazdon R L and Guariguata M R 2016 Natural regeneration as a toolfor large-scale forest restoration in the tropics: prospects and challenges *Biotropica* **48** 844–55

Chazdon R L and Uriarte M 2016 Natural regeneration in the contextof large-scale forest and landscape restoration in the tropics *Biotropica* **48** 709–15

Clewell A and McDonald T 2009 Relevance of natural recovery to ecological restoration *Ecol. Restor.* **27** 122–24

Corbin J D and Holl K D 2012 Applied nucleation as a forest restoration strategy *For. Ecol. 680 Manage.* **265** 37–46

Cury R T S and Carvalho O J 2011 Manual para restauração florestal: Florestas de transição (https://aliancadaterra.org/wp-content/uploads/2015/05/boas-praticas-05.pdf)

Dias L C P, Pimenta F M, Santos A B, Costa M H and Ladle R J 2016 Patterns of land use, extensification, and intensification of Brazilian agriculture *Glob. Change Biol.* **22** 2887

Durigan G *et al* 2010 Normas jurídicas para a restauração ecológica: uma barreira a mais a dificultar o êxito das iniciativas? *Revista Árvore Viçosa* **34** 471–85

Evans M C, Carwardine J, Fensham R J, Butler D W, Wilson K A, Possingham H P and Martin T G 2015 Carbon farming via assisted natural regeneration as a cost-effective mechanism for restoring biodiversity in agricultural landscapes *Environ. Sci. Policy* **50** 114–29

Gonzalez R C and Woods R E 2008 Digital Image Processing Third Edition

Instituto Nacional de Meteorologia INMET 2015 (www.inmet.gov.br/portal/index.php?r=bdmep/bdmep) (Acessed: December 2015)

Holl K D and Aide T M 2011 When and where to actively restore eco-systems? *For. Ecol. Manage.* **261** 1558–63

Holz S and Placci G 2005 Stimulating natural regeneration *Forest Restoration in Landscapes Beyond Planting Trees* ed S Mansourian, D Vallauri and N Dudley (New York, USA: Springer) pp 250–6

Hurtt G C, Thomas R Q, Fisk J P, Dubayah R O and Sheldon S L 2016 The impact of fine-scale disturbances on the predictability of vegetation dynamics and carbon flux *PLoS One* **11** e0152883

Instituto Estadual de Florestas IEF 2014 Relatório de Atividades 2013–2014 Programa Bolsa Verde (www.ief.mg.gov.br/images/stories/bolsaverde/2014/relatorio%20atividades%20bolsa%20verde%2013%2014.pdf) (Acessed: December 2015)

IMAFLORA 2008 Manual Técnico: Restauração e Monitoramento da Mata Ciliar e da reserva Legal para a Certificação Agrícola—Conservação da Biodiversidade na Cafeicultura (www.ambiente.sp.gov.br/municipioverdeazul/files/2011/11/Manual.pdf) (Accessed: December 2015)

Instituto Brasileiro de Geografia e Estatística IBGE 2006 Censo Agropecuário de 2006: Brasil, grandes regiões e unidades da federação: segunda apuração (ftp://ftp.ibge.gov.br/Censos/Censo_Agropecuario_2006/Segunda_Apuracao/censoagro2006_2aapuracao.pdf) (Accessed: December 2015)

International Institute for Sustainable IIS 2015 The Role of Natural Regeneration in Large-scale Forest and Landscape Restoration: Challenge and Opportunity (www.iis-rio.org/mwg internal/de5fs23hu73ds/progress?id=Pi6Ukd0AMTxYCxcaLgkxvC_BGiwoWVZfR-mqM3J49jM) (Accessed: December 2015)

Lamb D, Erskine P D and Parrotta J A 2005 Restoration of degraded tropical forest landscapes *Science* **310** 1628–32

Latawiec A E, Strassburg B B N, Brancalion P H S, Rodrigues R R and Gardner T A 2015 Creating space for large-scale restoration in tropical agricultural landscapes *Frontiers in Ecol. Environ.* **13** 211–18

Locatelli B, Catterall C P, Imbach P, Kumar C, Lasco R, Marín-Spiotta E, Mercer B, Powers J S, Schwartz N and Uriarte M 2015 Tropical reforestation and climate change: beyond carbon *Restoration Ecol.* **23** 337–43

Martins S V, Sartori M, Raposo Filho F R, Simoneli M, Dadalto G, Pereira M L and Silva A E S 2014a Potencial de regeneração natural de florestas nativas nas diferentes regiões do Estado do Espírito Santo (www.larf.ufv.br/wp-content/uploads/ES_ESTUDO_REGENERACAO_NATURAL_-_Completo_abr14.pdf) (Accessed: December 2015)

Martins S V, Sartori M, Raposo Filho F R, Simoneli M, Dadalto G, Pereira M L and Silva A E S 2014b manual de procedimentos gerais para a restauração florestal no estado do Espírito Santo (www.larf.ufv.br/wp-content/uploads/ES_MANUAL_DE-PROCEDIMENTOS-GERAIS-PARA-RESTAURAÇÃO-FLORESTAL-NO-ESTADO-DO-ES__abr14.pdf) (Accessed: December 2015)

Metzger J P and Brancalion P H S 2013 Challenges and opportunities in applying a landscape ecology perspective in ecological restoration: a powerful approach to shape neolandscapes *Nat. Conserv.* **11** 103–7

Ministério de Ciência Tecnologia e Inovação MCTI 2015 Terceiro Inventário Brasileiro De Emissões E Remoções Antrópicas De Gases De Efeito Estufa Relatório De Referência Emissões No Setor Uso Da Terra, Mudança Do Uso Da Terra E Florestas (Accessed: December 2016)

NASA LP DAAC2015ASTER Level 1 Precision Terrain Corrected Registered At-Sensor Radiance Version 3 NASA EOSDIS Land Processes DAAC USGS Earth Resources Observation and Science (EROS) Center Sioux Falls South Dakota (https://lpdaac.usgs.gov) (Accessed: January 2016)

Nunes F, Soares-Filho B S, Giudice R, Rodrigues H O, Bowman M S, Silvestrini R and Mendoza E 2012 Economic benefits of forest conservation: assessing the potential rents from Brazil nut concessions in Madre de Dios, Peru, to channel REDD+ investments *Environ. Conserv.* **39** 132–43

Nunez-Mir G C, Iannone B V, Curtis K and Fei S 2015 Evaluating the evolution of forest restoration research in a changing world: a 'big literature' review *New Forests* **46** 669–82

Pereira L, Oliveira C and Torezan J M D 2013 Woody species regeneration in Atlantic forest restoration sites depends on surrounding landscape *Nat. Conservacao* **11** 138–44

Pinto S R *et al* 2014 Governing and delivering a biome-wide restoration initiative: the case of Atlantic forest restoration pact in Brazil *Forests* **5** 2212–29

Prach K and Hobbs R J 2008 Spontaneous succession versus technical reclamation in the restoration of disturbed sites *Restor. Ecol.* **16** 363–6

Reis A, Bechara F C, Espíndola M B, Vieira N K and Souza L L 2003 Restauração de áreas degradadas: a nucleação como base para incrementar os processos sucessionais *Nat. Conserv.* **1** 28–36

Rezende C L, Uezu A, Scarano F R and Araujo D S D 2015 Atlantic Forest spontaneous regeneration at landscape scale *Biod. Conserv.* **24** 2255–227

Rodrigues R R, Gandolfi S, Nave A G, Aronson J, Barreto T E, Vidal C Y and Brancalion P H S 2011 Large-scale ecological restoration of high diversity tropical forests in SE Brazil *For. Ecol. Manage.* **261** 1605–13

Rodrigues R R, Lima R A F, Gandolfi S and Nave A G 2009 On the restoration of high diversity forests: 30 yr of experience in the Brazilian Atlantic Forest *Biol. Conserv* **142** 1242–51

Shono K, Cadaweng E A and Durst P B 2007 Application of assisted natural regeneration to restore degraded tropical forestlands *Restor. Ecol.* **15** 620–6

Silva C C 2013 Potencial de espécies nativas para a produção de madeira serrada em plantios de restauração florestal *Master Degree Dissertation* Universidade Estadual de São Paulo, Brasil

Soares-Filho B S, Rajão R, Macedo M, Carneiro A, Costa W, Coe M, Rodrigues H and Alencar A 2014 Cracking Brazil's Forest Code *Science* **344** 363–4

Soares-Filho B S, Rajão R, Merry F, Rodrigues H, Davis J, Lima L, Macedo M, Coe M, Carneiro A and Santiago L 2016 Brazil's market for trading forest certificates *Plos One* **11** e0152311

Soares-Filho B S *et al* 2013a SimMinas: Uma plataforma integrada de modelagem de mudanças no uso da terra, emissões de CO_2 associadas e impactos ambientais para o estado de Minas Gerais

Soares-Filho B S, Rodrigues H and Follador M 2013b A hybrid analytical-heuristic method for calibrating land-use change models *Environ. Modell Software 2013* **43** 80–87

Society for Ecological Restoration Science & Policy Working Group—SER 2004 The SER Primer on Ecological Restoration, Tucson (www.ser.org/.) (Acessed: December 2015)

Stanturf J A, Palik B J and Dumroese R K 2014 Contemporary forest restoration: a review emphasizing function *For. Ecol. Manag.* **331** 292–323

Stickler C M, Nepstad D C, Azevedo A A and McGrath D G 2013 Defending public interests in private lands: compliance, costs and potential environmental consequences of the Brazilian forest code in Mato Grosso *Philos. Trans. R. Soc. London Ser. B* **368** 20120160

The Nature Conservancy TNC 2013 Manual de Restauração Florestal: Um Instrumento de Apoio à Adequação Ambiental de Propriedades Rurais do Pará (www.nature.org/media/brasil/manual-de-restauracao-florestal.pdf) (Accessed: December 2015)

The World Bank Group 2010 Brazil Low-carbon Country Case Study (http://siteresources.worldbank.org/BRAZILEXTN/Resources/Brazil_LowcarbonStudy.pdf) (Accessed: December 2016)

Wendland K J, Honzak M, Portela R, Vitale B, Rubinoff S and Randrianarisoa J 2010 Targeting and implementing payments for ecosystem services: opportunities for bundling biodiversity conservation with carbon and water services in madagascar *Ecol. Econ.* **69** 2093–107

Wheeler C E, Omeja P A, Chapman C A, Glipin M, Tumwesigye C and Lewisa S L 2016 Carbon sequestration and biodiversity following 18 yr of active tropical forest restoration *For. Ecol. Manage.* **373** 44–55

Wunscher T, Engel S and Wunder S 2008 Spatial targeting of payments for environmental services: a tool for boosting conservation benefits *Ecol. Econ.* **65** 822–33

Zoneamento Ecológico do Estado de Minas Gerais 2006 (www.zee.mg.gov.br/) (Acessed: December 2015)