FELIPE SANTOS DE MIRANDA NUNES

MODELAGEM E GOVERNANÇA DAS POLÍTICAS DE MITIGAÇÃO DAS MUDANÇAS CLIMÁTICAS E RESTAURAÇÃO ECOLÓGICA NO ESTADO DE MINAS GERAIS

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Meteorologia Aplicada, para obtenção do título de *Doctor Scientiae*.

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À minha família

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BIOGRAFIA

FELIPE SANTOS DE MIRANDA NUNES, filho de Marlio de Miranda Nunes e Maria de Lourdes Santos Nunes, nasceu em 30 de agosto de 1983, na cidade de Belo Horizonte-MG.

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SUMÁRIO

RESUMO

NUNES, Felipe Santos de Miranda, D.Sc., Universidade Federal de Viçosa, julho de 2016. **Modelagem e governança das políticas de mitigação das mudanças climáticas e restauração ecológica no estado de Minas Gerais**. Orientador: Britaldo Silveira Soares Filho. Coorientadores: Raoni Guerra Lucas Rajão e Aristides Ribeiro.

A elaboração e implementação de políticas de combate às mudanças climáticas e restauração ecológica representam grandes desafios para a modelagem e governança ambiental e tem atraído cada vez mais atenção da ciência e da política. No campo da modelagem científica, o uso de modelos computacionais para caracterização dos problemas sócio-ecológicos, simulação de trajetórias futuras e avaliação *ex-ante* de intervenções tem se destacado na produção de conhecimento “politicamente relevante”. Entretanto, as diferentes escalas espaciais e temporais das soluções a serem modeladas e os processos decisórios requerem ferramentas cada vez mais customizadas. Na esfera política, os modelos podem desempenhar um papel relevante quando orientados para indentificar problemas ambientais, estimar impactos econômicos e avaliar a relação custo-efetividade das medidas propostas. Contudo, apesar dos formuladores de políticas buscarem soluções baseadas na “melhor” ciência disponível, os resultados desses modelos raramente se traduzem diretamente em políticas públicas. Esta tese visa contribuir para a literatura apresentando diferentes perspectivas científicas acerca da modelagem e governança para viabilização de políticas de mitigação das mudanças climáticas e restauração ecológica (florestal) no estado de Minas Gerais, Brasil. No campo da modelagem, em um estudo para se estimar custos e benefícios da regeneração da vegetação nativa a partir de diferentes métodos de restauração, um modelo de otimização espacialmente explícito foi elaborado para análise do potencial do novo Código Florestal. Os resultados mostram que 1,5 milhão de hectares ou 75% do passivo florestal estadual pode ser restaurado a um custo de US$ 776±137 milhões em um período de 20 anos, empregando métodos de restauração de baixo custo, como restauração passiva e regeneração natural assistida. Isto resultaria em um sequestro potencial de 284 $MtCO_2e$. Ao incluir métodos de plantio de espécies nativas necessários para restaurar áreas altamente degradadas, os custos podem alcançar US$ 1,7±0,3 bilhões. Se contabilizarmos os custos de oportunidade de uso da terra, esse valor aumentaria para US$ 4,8±1,5 bilhões. A inclusão desses métodos recuperaria 2 milhões de hectares, resolvendo integralmente o passivo florestal e resultando em um sequestro potencial de 345 $MtCO_2e$. As estimativas enfatizam a necessidade de formatar e implementar políticas regionais que aproveitem o potencial de regeneração natural na paisagem, a fim de reduzir os custos de conformidade legal e priorizar a restauração de áreas chave para serviços ecossistêmicos, incluindo estoque de carbono, água e biodiversidade. Adicionalmente, visando contribuir para uma literatura pouco explorada na fronteira entre ciência e política, é apresentado um estudo que detalha e analisa de forma reflexiva as práticas necessárias para elaboração (e viabilização) do Plano de Energia e Mudanças Climáticas de Minas Gerais. A partir de uma perspectiva interpretativista associada à escola de estudos da ciência e tecnologia (TS), a pesquisa exemplifica o papel dos modelos na formação, legitimação, busca de consenso e tomada de decisão de políticas públicas. Empiricamente releva como o conhecimento científico pode ser selecionado e comunicado pelos formuladores de políticas ambientais e como a necessidade de seguir protocolos governamentais em organizações que atuam na interface ciência-política pode levar a políticas menos ambiciosas. Com base na observação participativa, análise documental e entrevistas com diferentes formuladores de políticas e partes interessadas, o artigo argumenta que a elaboração de políticas ambientais na interface ciência-política requer não só o uso de modelos científicos capazes de legitimar a discussão das soluções, mas também a habilidade de trazer a “verdade para o Poder” e a capacidade de antecipar e evitar obstáculos políticos. Ao abordar simultaneamente a elaboração e utilização de modelos computacionais para proposição de políticas subnacionais, este estudo contribui para lançar luz sobre a lacuna entre a concepção e uso dos modelos, sob a ótica do pesquisador e do formulador de políticas. O estudo pode servir ainda de guia para indicar as áreas prioritárias para a implementação de políticas e projetos de restauração

em larga escala e orientar o desenvolvimento de trabalhos de fronteira entre cientistas e formuladores de políticas ambientais.

ABSTRACT

NUNES, Felipe Santos de Miranda, D.Sc., Universidade Federal de Viçosa, July, 2016. **Modeling and governance of climate change mitigation and ecological restoration policies in Minas Gerais state**. Adviser: Britaldo Silveira Soares Filho. Co-advisers: Raoni Guerra Lucas Rajão and Aristides Ribeiro.

The design and implementation of climate change mitigation and ecological restoration policies represent major challenges for environmental modeling and governance and have attracted an increasing science and policy attention. In the field of modeling, the use of computer models to characterize socio-ecological problems, simulate future trajectories, and *ex-ante* assess interventions have been highlighted for policy-relevant knowledge production. However, different spatial and temporal scales of solutions to be modeled and decision making processes often require more customized tools. In the field of policy, models can play an important role when oriented to define environmental problems, estimate economic impacts, and assess the cost-effectiveness of the measures. Nevertheless, despite policy makers seek solutions based on the "best" available science, model results are rarely translated directly into public policies. This thesis aims to contribute to the literature presenting different scientific perspectives on environmental modeling and governance for enabling policies to tackle climate change and promote ecological (forest) restoration in Minas Gerais state, Brazil. From a modeling standpoint, in a study to estimate costs and benefits of native vegetation regeneration under different restoration methods, a spatially-explicit optimization model was developed to analyze the potential of the new Forest Code. The results show that 1.5 million hectares or 75% of the Forest Code debt in Minas Gerais can be restored at a cost of US$ 776±137 million over a 20 year-period by employing low-cost restoration methods such as passive restoration and assisted natural regeneration. This would result in a potential sequestration of 284 $MtCO_2e$. When adding planting methods needed to restore highly degraded areas, costs would reach US$ 1.7±0.3 billion. If we then account for the land-use opportunity costs this number increases further to US$ 4.8±1.5 billion. The addition of these methods would recover 2 million hectares, fully solving the Forest Code debt and resulting in a potential sequestration of 345 $MtCO_2e$. The estimates emphasize the need to design and implement regional policies that take advantage of the natural regeneration potential across the landscape in order to lower the costs of compliance as well as prioritize the restoration of areas key to ecosystem services, namely carbon, water, and biodiversity. In addition, in order to contribute to a poorly explored literature on boundary work at science-policy interface, it is presented a study that details and analyze reflectively the practices necessary to elaborate (an enable) the Minas Gerais Climate and Energy Plan. From an interpretative perspective associated with science and technology studies (STS), the research illustrates the role of models in agenda-setting, legitimation, consensus-building and decision making on environmental policies. Empirically reveals how scientific knowledge can be selected and communicated by environmental policy makers and how the need to follow government protocols in organizations working in the science-policy interface can lead to less ambitious policies. Based on participant observation, document analysis, and interviews with policy makers and stakeholders, the article argues that the development of environmental policies in the science-policy interface not only requires the use of scientific models capable of legitimizing the discussion of solutions, but also the ability to bring ‘truth to power’ and the capacity to anticipate and avoid political obstacles. By addressing simultaneously the development and the use of computer models for sub-national policy making, this study helps to shed light on the gap between the design and use of models, from the viewpoint of the researcher and the policy maker. The study can also serve as guide to point out priority areas for carrying out large-scale restoration projects and policies and orient the development of boundary work agendas between scientists and environmental policy makers.

INTRODUÇÃO

A urgência no combate às mudanças climáticas e restauração dos processos ecológicos representam grandes desafios para a humanidade e tem atraído cada vez mais atenção da ciência e da política. Em seu compromisso nacionalmente determinado (NDC) submetido à 21ª Conferência das Partes (COP), o Brasil estabeleceu um conjunto de metas ambiciosas para redução de 43% das emissões de gases de efeito estufa em 2030, com destaque para o reflorestamento e restauração de 12 milhões de hectares (Brazil, 2015). Apesar de pairarem dúvidas quanto à viabilidade da NDC (Rajão e Soares-Filho, 2015), o cumprimento das metas exigirá avanços na fronteira da ciência e prática de uma economia de baixo carbono, ferramentas robustas para a tomada de decisão e políticas subnacionais para promoção da regeneração da vegetação nativa em larga escala. Esta última é crucial tanto para a consecução dos objetivos previstos na NDC quanto para a implementação do novo Código Florestal (Lei Nº 12.727, de 17 de outubro de 2012).

No campo das ciências ambientais, o uso de modelos computacionais para avaliação de políticas públicas e apoio ao processo decisório tem ganhado cada vez mais espaço apesar da insuficiente representação da dimensão ecológica (Harfoot et al., 2014; Farmer et al., 2015; Hackett e Moxnes, 2015). O amplo espectro de ferramentas desenvolvidas varia de modelos de complexidade reduzida a modelos que incluem o maior número de elementos e interações que os recursos computacionais permitem processar (Verburg et al., 2015). Diferentes abordagens como os modelos baseados em agentes (Farmer e Foley, 2009; Morgan e Daigneault, 2015), equilíbrio geral computável (Timilsina e Mevel, 2013; Suttles et al., 2014), autômatos celulares (Soares-Filho et al., 2013; Gaudreau et a., 2016) e sistemas dinâmicos (Xavier et al., 2013; Fangzheng et al., 2015) tem se destacado na produção de conhecimento relevante para a política.

Nas últimas décadas houve um expressivo avanço na simulação de fatores socioeconômicos e ambientais por meio da integração de diferentes disciplinas (por exemplo, agricultura, ecologia, sociologia, hidrologia, economia e climatologia), reforçando o papel da modelagem como instrumento científico para ampliar a compreensão e representação de fenômenos relacionados às mudanças climáticas e evolução dos processos ecológicos (veja, por exemplo: Gough et al., 1998; Oxley et al., 2004; Pahl-Wostl, 2007; Kragt et al., 2011; Kelly et al., 2013; Harmsen et al., 2015). Na escala global, os modelos de avaliação integrada (Rana e Morita, 2000; Schwanitz, 2013) dominam os estudos científicos exploratórios, sendo utilizados para simular trajetórias futuras e avaliar possíveis soluções (Verburg et al., 2015). No entanto, em escalas regionais, como no caso de governos subnacionais, esses modelos geralmente não estão configurados para capturar e representar as dinâmicas e processos locais.

Apesar da variedade de paradigmas de pesquisa (Burrel e Morgan, 1979; Geels, 2010) percebe-se uma ampla aplicação da teoria econômica (neoclássica), tanto nos modelos de avaliação, construídos para avaliar políticas específicas, quanto nos modelos de otimização, programados para encontrarem a “melhor solução”, geralmente definida com base em um ponto de vista de eficiência econômica (Nordhaus e Sztorc, 2013). Nesse paradigma dominante, encontramos com frequência abordagens baseadas na avaliação de custo-benefício (Cai et al., 2015; Plank et al., 2016), custo-efetividade (Bakam et al., 2012; Saujot e Lefèvre, 2016) e curvas de custo de abatimento de emissões de gases de efeito estufa (Levihn et al., 2014; Jones et al., 2015).

Mais recentemente alguns modelos têm aplicado abordagens mais integradoras para análise do impacto de políticas de uso da terra (Soares-Filho et al., 2014; Soares-Filho et al., 2016), mapeamento e gestão de serviços ecossistêmicos (Costanza et al., 2014; Hackett e Moxnes, 2015) e mensuração da restauração do capital natural (Orsi et al., 2011; Blignaut et al., 2014), revelando linhas de pesquisa promissoras para avaliação de políticas em larga escala.

Além de permitirem avanços científicos, os modelos podem desempenhar diferentes papéis na governança de políticas ambientais, como a identificação do problema e formação de agenda, legitimação de temas e atores, criação de consenso e priorização de recursos (Van Daalen et al., 2002). Notadamente, os cenários preditivos são utilizados para criar consciência social de desafios futuros (Pielke, 2003) e enquadrar problemas ambientais como questões econômicas e políticas (Hoppe and Wesselink, 2014). Entretanto, apesar dos modelos serem utilizados nos processos decisórios, com o argumento de representarem o melhor conhecimento disponível, seus resultados raramente se traduzem diretamente em políticas públicas como sugerido por grande parte dos cientistas ambientais e economistas (Esty, 2004; Morecroft et al., 2014).

Devido ainda à falta de sintonia (e ambição) entre as políticas e a urgência reivindicada pela ciência, alguns pesquisadores têm apontado a existência de uma lacuna entre a produção científica e as necessidades da sociedade (Rapley e Meyer, 2014; Rose, 2014). A partir desta constatação, há um debate em curso se a melhor abordagem a ser adotada reside em demarcar fortemente as fronteiras entre ciência e política e melhorar a comunicação (Morecroft et al., 2014), incorporar conceitos ligados às ciências sociais (políticas) cruzando as fronteiras disciplinares (Castree et al., 2014) ou mesmo abandonar o "modelo linear "(Rose, 2014), em que "a ciência fala a verdade ao Poder" (Hoppe, 2010b; Wesselink e Hoppe, 2013).

Nesse debate, é essencial reconhecer que muitas das políticas a serem apoiadas pelos modelos são incertas, dependentes de preferências locais e alvo de contestações científicas (Rauschmayer e Wittmer, 2006). Todavia, dado o potencial dos modelos de fornecer um meio de estruturar e explorar problemas e de gerar informações para análise e caracterização de espaços de decisão, é essencial para os pesquisadores compreender e interagir com processos de tomada de decisão (McIntosh et al., 2008). Sob esta perspectiva, a literatura demonstra a necessidade de maior investigação da lacuna entre “concepção e uso dos modelos" (Jakeman et al., 2008; Schmolke et al., 2010; Sohl e Claggett, 2013), sendo esta também uma oportunidade para aprimorar o desenvolvimento dessas ferramentas (McIntosh et al., 2008).

Portanto, para se ampliar a compreensão e efetividade da modelagem científica como instrumento de governança ambiental são necessárias duas abordagens: (1) desenvolver modelos orientados para simular e avaliar soluções nas escalas apropriadas (Verburg et al., 2015), gerando assim conhecimento “relevante” para a política; e (2) avançar no entendimento da fronteira entre a ciência e a política

(Hoppe, 2008), analisando de forma reflexiva como os modelos e resultados científicos são utilizados e comunicados pelos formuladores de políticas.

No intuito de contribuir para a literatura em ambas as frentes de conhecimento, esta tese é dividida em dois capítulos que apresentam distintas e complementares perspectivas científicas acerca da modelagem e governança de políticas de mitigação das mudanças climáticas e restauração ecológica no estado de Minas Gerais, Brasil. Ao abordar simultaneamente a elaboração e utilização de modelos para suporte à tomada de decisão em políticas regionais, contribui para lançar luz sobre o debate acerca da lacuna “concepção e uso dos modelos” sob a ótica do pesquisador e do formulador de políticas. Esta última um ponto de vista ainda muito pouco explorado na literatura científica (Hoppe, 2010a).

No primeiro capítulo, em razão dos raros estudos e modelos quantitativos para subsidiar políticas de restauração ecológica na escala da paisagem (Vogler et al., 2015), um modelo de otimização espacial foi elaborado para estimar custos e benefícios da regeneração da vegetação nativa a partir de diferentes estratégias de restauração previstas no novo Código Florestal. O estudo visa fornecer aos formuladores de políticas as oportunidades geográficas e a magnitude dos esforços privados e públicos necessários para promover a restauração em larga escala em Minas Gerais.

A partir da espacialização do potencial de regeneração natural são estimados os custos globais e a efetividade em termos de regularização do passivo florestal e sequestro de carbono em uma perspectiva de eficiência econômica no espaço-tempo. Os resultados reforçam o papel da regeneração natural na redução substancial do custo da restauração em larga escala (Chazdon e Guariguata, 2016). Adicionalmente, são apontadas áreas prioritárias para restauração visando a provisão de serviços ecossistêmicos, como estoque de carbono, proteção de recursos hídricos e biodiversidade.

No segundo capítulo, a partir de uma perspectiva interpretativista associada aos estudos da ciência e tecnologia (Jasanoff, 1990; Hackett et al., 2007; Hoppe, 2008), é apresentada uma pesquisa que detalha e analisa as práticas necessárias para elaboração (e viabilização) do Plano de Energia e Mudanças Climáticas de Minas Gerais. Estendendo uma literatura pouco explorada sobre fronteira entre ciência e política no nível organizacional (Guston, 2001; White et al., 2010; Boezeman et al., 2013), o estudo exemplifica o papel de modelos na formação, legitimação, busca de consenso e tomada de decisão política. Empiricamente revela como o conhecimento científico pode ser selecionado e comunicado pelos formuladores de políticas e como a necessidade de seguir protocolos governamentais em organizações que atuam na interface ciência-política pode levar a políticas menos ambiciosas.

Com base na observação participativa, análise documental e entrevistas com formuladores de políticas e partes interessadas, o estudo argumenta que a elaboração das políticas ambientais na interface ciência-política requer não só o uso de modelos científicos capazes de legitimar a discussão das soluções, mas também a habilidade de trazer a "verdade para o Poder" e a capacidade de antecipar e evitar obstáculos políticos.

Por fim, na conclusão é feita uma reflexão sobre os principais resultados de ambos os estudos em termos de complementariedades, limitações e avanços na compreensão da modelagem e governança ambiental para viabilização de políticas públicas em esfera subnacional.

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CAPÍTULO 1

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 key for meeting the targets of its National Determined Contribution (NDC). The feasibility of this goal, however, remains uncertain due to a paucity of information on its economics and implementation challenges. Here, we begin to fill this gap by applying a spatially-explicit model for Minas Gerais state in Brazil to estimate costs and benefits of native vegetation regeneration under different restoration approaches. Our results show that 1.5 million hectares or 75% of the Forest Code debt in Minas Gerais can be restored at a cost of US$ 776±137 million over a 20 year-period by employing low-cost restoration methods such as passive restoration and assisted natural regeneration. This would result in a potential sequestration of 284 $MtCO_2e$. When adding replanting methods needed to restore highly degraded areas, costs would reach US$ 1.7±0.3 billion. If we then account for the land-use opportunity costs this number increases further to US$ 4.8±1.5 billion. The addition of these methods would recover 2 million hectares, fully solving the Forest Code debt and resulting in a potential sequestration of 345 $MtCO_2e$. Our results emphasize the need to design and implement regional policies that take advantage of the natural regeneration potential across the landscape in order to lower the costs of compliance as well as prioritize the restoration of areas key to ecosystem services, namely carbon, water, and biodiversity.

1. Introduction

As part of its Nationally Determined Contribution to mitigate climate change (NDC) (Brazil 2015), Brazil established a target of reforesting and restoring 12 million hectares (Mha) by 2030. If fully implemented, this policy will position Brazil as a world leader in reforestation and native vegetation regeneration. However, the challenges to meet this target are enormous. The area targeted for restoration or reforestation is roughly equivalent in size to England and will require a large effort sharing between national and subnational governments.

Despite the large amnesty granted to past deforesters by the revisions in the recently updated Forest Code (FC) (Soares-Filho *et al* 2014), there are still 24 Mha of private land to be restored to solve the FC debt—past illegal deforestation (Soares-Filho *et al* 2016) —, of which 2 Mha are in Minas Gerais. Aside from trading forest certificates (in Portuguese CRA, meaning environmental forest quotas), whereby an area to be restored can be offset on other rural properties that have more native vegetation than required by the FC (Soares-Filho *et al* 2016), the law allows the utilization of different mixes of restoration methods. The range of options includes from natural regeneration, replanting exclusively native species, to replanting an intermix of exotic and native species. Hence, the choice of one portfolio of restoration methods will incur not only to costs to the government and landowners, but also to benefits to the environment.

Currently, there is no economic estimation of the global costs, including private and government, for such an initiative at a state level. There are, however, local estimates of mixes of restoration methods that range from US$ 700 (IIS 2015) to more than US$ 4500 per hectare (Rodrigues *et al* 2009). Since these costs are prohibitive to most individual landowners, there is a need to develop regional policies that take advantage of the natural regeneration potential in order to lower the costs of compliance. To help accomplish this goal, we quantify the natural regeneration potential across the state of Minas Gerais, Brazil, providing estimates of costs of large-scale restoration of the native vegetation under different restoration methods. Our study also estimates environmental benefits in the form of carbon sequestration, pointing out priority areas relevant to ecosystem services, such as carbon, water, and biodiversity.

1.1. Forest restoration methods

Reforestation has been widely recognized as an important action to mitigate climate change (Chazdon 2008, Locatelli *et al* 2015), enhance ecosystem services (Wunscher *et al* 2008, Wendland *et al* 2010, Alexander *et al* 2016), improve forest habitat and thus biodiversity (Birch *et al* 2010), and sustain the livelihoods of traditional populations (Nunes *et al* 2012). As such, the adoption of reforestation and native vegetation recovery strategies under an ecological restoration perspective has gained momentum (SER 2004, Stanturf *et al* 2014, Nunez-Mir *et al* 2015).

Restoration strategies can be classified into two groups: passive and active (Holl and Aide 2011). 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. By contrast, active restoration is generally carried out through interventionist practices, such as sowing and planting seedlings, in order to set a desired restoration trajectory (Holl and Aide 2011, Rodrigues *et al* 2011, Brancalion *et al* 2016). This increased silvicultural intervention comes at a cost, however; common planting approaches utilized in the Brazilian Atlantic Forest, for example, range from US$ 3,000 to over US$ 4,500 per hectare (Rodrigues *et al* 2009, BNDES 2015). To cope with the high costs of active restoration, 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)—, including the prevention and control of fire and invasive species (Shono *et al* 2007, Evans *et al* 2015).

ANR is an intermediate approach that employs techniques to assist the natural re-establishment of vegetation (Corbin and Holl 2012). Although, ANR techniques may be less effective than planting for enhancing floristic diversity at the initial stages (Shono *et al* 2007, Bechara *et al* 2016), they offer relevant cost advantages when compared to planting seedlings (Shono *et al* 2007). Nevertheless, they seldom work if applied to deeply degraded sites or areas previously submitted to intense land use (i.e., mechanized agriculture), which have already surpassed a new state ecological threshold (Lamb *et al* 2005, Chazdon 2008, Chazdon 2013). To deal with those areas, plantations covering the entire area (Rodrigues *et al* 2011, Brancalion *et al* 2016) as well as techniques involving the planting small patches of trees (partial planting) to serve as focal areas for recovery (Corbin and Holl 2012, Bechara *et al* 2016) have been recommended. Thus, active restoration comprises a range of techniques, that fall roughly into the classification: 1) ANR, 2) partial planting (PARPLAN) and 3) total planting (TOTPLAN), all of which can be combined to vary the level of intervention according to the site favorability, management goals, and available financial resources (Chazdon 2008, Rodrigues *et al* 2011, Bechara *et al* 2016).

The success of a restoration project is thus a matter of where and when to use each one or a combination of restoration methods (Prach and Hobbs 2008, Clewell and McDonald 2009, Holl and Aide 2011). In tropical areas, such as Brazil, different passive and active methods have been proposed (IMAFLORA 2008, Rodrigues *et al* 2009, Cury and Carvalho 2011, TNC 2013, Bechara *et al* 2016, Brancalion *et al* 2016), 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, Brancalion *et al* 2016). 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).

1.2. The role of natural regeneration in forest restoration

Forest ecosystems may regenerate to previously forest state once barriers to natural regeneration are removed, i.e., grazing (Holz and Placci 2005, Chazdon 2008). 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 (Chazdon 2008) to sustain local biodiversity and biotic interactions (Chazdon and Guariguata 2016). Assisting natural regeneration usually leads to lower implementation costs than replacement planting approaches, making it a strategic option for large-scale projects (Holz and Placci 2005, Chazdon and Uriarte 2016, Chazdon and Guariguata 2016).

The increased forest cover in some tropical areas (Aide *et al* 2013, Chazdon and Guariguata 2016) is a demonstration that natural regeneration plays a major role in restoration. The recovery process, however, can take place very slowly or be inhibited in degraded agroecosystems (Holz and Placci 2005, Brancalion *et al* 2016). Natural regeneration is affected by local resource availability (i.e., soil moisture) (Holl and Aide 2011, Chazdon and Guariguata 2016), prior land use intensity (Rodrigues *et al* 2011, Chazdon 2014), and dispersal of propagules (i.e., seeds and sprouts) (Pereira *et al* 2013, Chazdon and Guariguata 2016). In this respect, abandoned pasturelands with high local resource availability (i.e., soil nutrients, seed bank, and sprouts) near forest remnants may be restored passively at a relatively low cost. On the other hand, pastures with eroded and compacted soils may require partial or total planting that demands substantial investments. The main challenge for forest restoration is, therefore, to evaluate the site and landscape potential for natural regeneration and, if necessary, to specify what techniques would be the most cost-effective in helping expedite the natural regeneration processes (Holz and Placce 2005).

Despite its economic and environmental advantages, natural regeneration is often neglected when reforestation and restoration policies are formulated and there is still a dearth of knowledge about where natural regeneration could take a major role in large-scale restoration (Chazdon and Guariguata 2016). 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).

1.3. 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.

Minas Gerais needs one of largest restoration effort in Brazil to comply with the FC. In total 0.65 Mha in Permanent Preservation Riparian areas (PPR)—a buffer area of native vegetation on each side of water stream—and 1.3 Mha of Legal Reserves (LR)—a fraction of the rural property that must be maintained as native vegetation—need to be restored (Soares-Filho *et al* 2014). Solving the FC debt of Minas Gerais thus is pivotal for the success of the National Plan for Recovering Native Vegetation (PLANAVEG), which seeks to recover 12.5 Mha nationally in 20 years 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. The 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 was used together with maps of land use, land prices, and the FC balance (levels of compliance) as inputs for a spatial optimization model that computes the natural regeneration potential for each microwatershed—at the 12th-order (ANA 2010). To pinpoint key ecological restoration zones, we superimposed the 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 the Environmental Compliance Program (Programa de Regularização Ambiental, or PRA, in Portuguese), which allows 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) and three active methods (ANR, PARPLAN, and TOTPLAN) to solve the forest debt across the state. To calculate the total restoration costs, we added 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 an 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. Economic analyses are presented as marginal abatement cost curves (Figure 1).

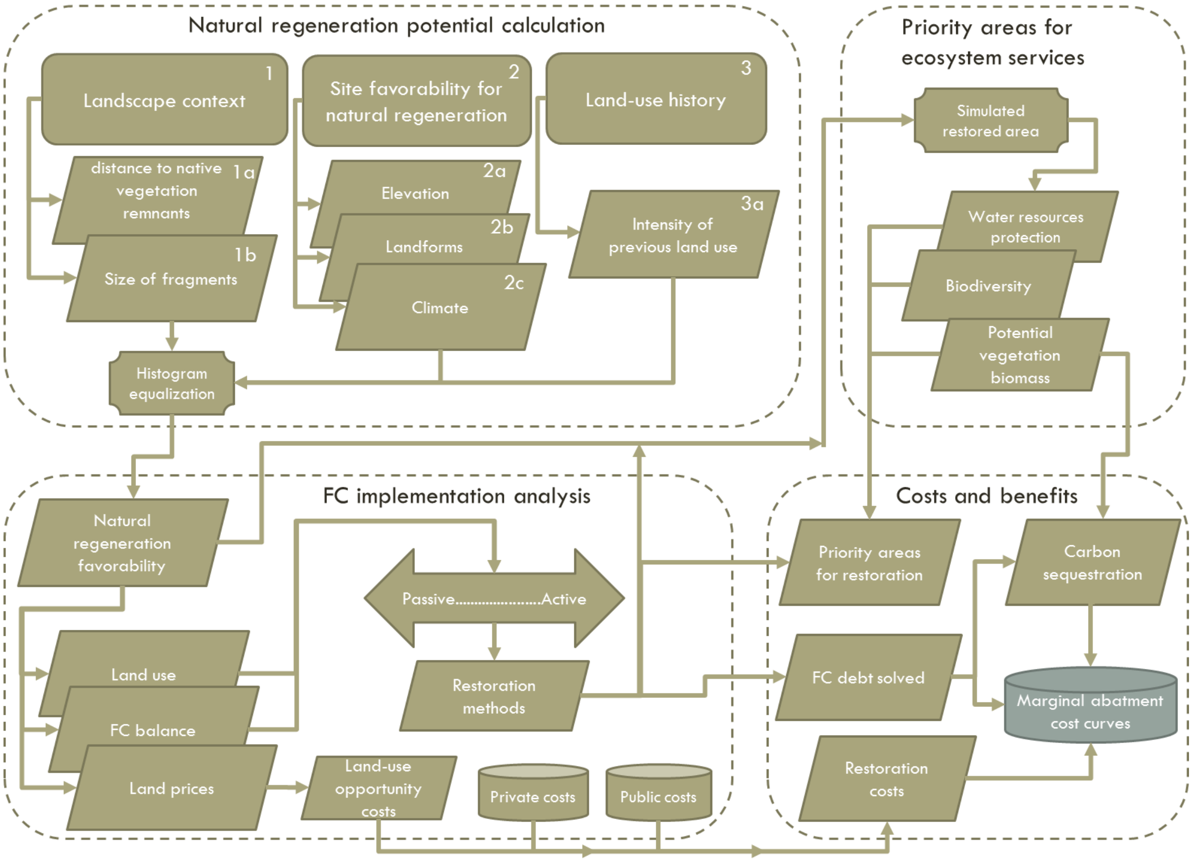

Figure 1: Modeling flowchart highlighting the main analysis modules (dashed lines) and their steps and inputs.

2.2. Data

Our dataset comes from various sources (Table S1). 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 governments 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 facilitate passive restoration (Holl and Aide 2011). They include: 1) the landscape context, i.e., the surrounding land use matrix that serves as an important source of propagules (Holl and Aide 2011, Rodrigues *et al* 2011, Martins *et al* 2014a); 2) site favorability for natural regeneration, such as elevation, landform, and climate (Holl and Aide 2011, Magnago *et al* 2012, Martins *et al* 2014a); and 3) land-use history (Holl and Aide 2011, Rodrigues *et al* 2011, Martins *et al* 2014a). 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).

With respect to the landscape context (1), 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 (1a) the Euclidean distance to fragments of native vegetation and then normalizes these values into a standard range of favorability. In addition, the model estimates the region of influence for each fragment of native vegetation based on its size (1b), assigning all map cells to their nearest fragment. 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 (2), differences in elevation contribute to the dispersal of propagules as it favors the local seed availability in lower areas (Martins *et al* 2014a). Thus, to calculate the influence of elevation (2a), we superimposed the hilltop map (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. Next, we identified landform forms (2b) that favor natural regeneration. 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 (Holl and Aide 2011, Martins *et al* 2014a). To this end, 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 influence positively the rate of natural regeneration (Holl and Aide 2011, Martins *et al* 2014a). Then, we used a 30-year annual average precipitation map (INMET 2015) for determining the local influence of climate.

The rate of forest recovery is also influenced by the land-use history, i.e. level of local degradation or land use intensity (Holl and Aide 2011). Both the intensity and duration of past land use can affect negatively the soil properties and the availability of propagules locally (Holl and Aide 2011). Hence, to quantify the influence of land-use history (3), we used the map of historical land use (1940–2012) from Dias *et al* (2016) to estimate (3a) the previous intensity of land use.

Then, 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 again equalized to generate an integrated favorability map (1-100) for the potential of natural regeneration. As a result, our fine spatial resolution approach (60x60m) enables the assessment of the integrated influence of key landscape features on the local natural regeneration potential as indicated by ecological restoration studies (Rodrigues *et al* 2011, Holl and Aide 2011, Martins *et al* 2014a) and technical manuals for Brazilian biomes (IMAFLORA 2008, Martins *et al* 2014b, BIOFLORA 2015).

2.4. Analyzing forest restoration under the FC implementation

The 60x60m 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 only on pasturelands 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). The model then allocates the amount of restoration required by the FC within a microwatershed (Figure S2) selecting the appropriate restoration method according to the level of natural regeneration favorability previously calculated (Table 1). The set of methods selected therefore 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).

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 regeneration (0 - 100)
1) Passive restoration (PASRE)	Site isolation from human disturbances	> 75
2) Assisted natural regeneration (ANR)	Resprout protection and control of invasive species	50 to 75
3) Partial planting (PARPLAN)	Planting seedlings in islands (small patches)	25 to 50
4) Total planting (TOTPLAN)	Planting seedlings covering the entire area	< 25

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 disbursement schedule of three years (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 depends also on the shape and size of a restoration parcel. We assume that the LR parcels approximate a square, and are fenced on three sides, on average, and the PPR parcels approximate a linear shape and are fenced on two sides, on average. The cost of fencing for LR 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 varies linearly with the size of PPR.

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

Restoration methods	Private costs of implementation and maintenance per hectare (thousand US$)
1) Passive restoration (PASRE)	0.63 ± 0.17
2) Assisted natural regeneration (ANR)	1.23 ± 0.17
3) Partial planting (PARPLAN)	2.57 ± 0.49
4) Total planting (TOTPLAN)	3.63 ± 0.94

A discount rate of 8% was used for calculating Net Present Values (NPV) (World Bank 2010) over a 20-year period required in the PRA. We estimated the total private costs considering that 10% of the FC debt will be restored every 2 years as required by the law. The cost curves were calculated for the private costs in NPV. Since the FC implementation requires also verification and monitoring actions, 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 were then discounted using the same discount rate. 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 local difference between pastureland prices (Figure S3) and forested land prices (Figure S4). To compose the global budget, we sum the private and public costs to solve the FC debt and the opportunity costs of compliance.

We also estimated the potential benefits of forest restoration in terms of carbon sequestration. To do so the model deducts the areas appropriate for each restoration method from the total area requiring restoration (both PPR and LR), 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 (Soares-Filho *et al* 2016) over the areas restored under each method to quantify the carbon removal over a 20 year-period (Figure S5). We assumed a recovery threshold of 44% of the potential biomass for the 20-year of restoration period and a biomass carbon content of 50% (MCTI 2015).

2.6 Prioritizing areas to enhance ecosystem services

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 (biodiversity) (Figures S7 e S8) to pinpoint priority restoration areas for enhancing ecosystem services.

3. Results

We estimate that approximately 30% (8 Mha) of the total pasturelands in the State 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 debts could be solved by employing only PASRE and 75% (1.5 Mha) by adding ANR (Figure 3). Private costs to meet these targets would amount to US$ 175±47 and US$ 715±135 million, respectively (Table 3). These areas would then represent 6% and 12% of the Brazil´s NDC restoration target. The remaining 25% of the FC requirement is located in regions with low natural regeneration potential and thus need the employment of PARPLAN and TOTPLAN methods. Although covering a small fraction of the FC debt, the costs of recovering these areas represent 55% of the total private costs due to high costs of implementation and maintenance (Table 3).

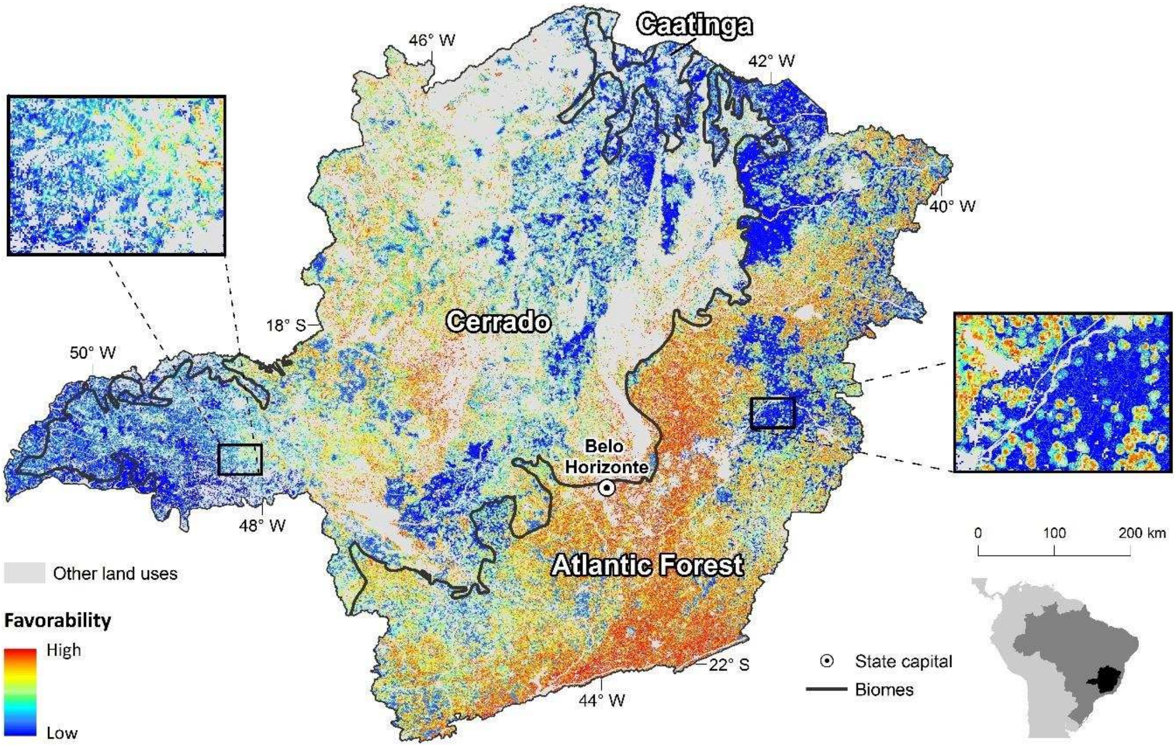

Figure 2: Favorability for natural regeneration on pasturelands of Minas Gerais.

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)
1) PASRE	715	175±47	30±1	1.4±0.4
2) ANR	763	540±88	31±1	1.6±0.6
3) PARPLAN	268	398±75	11±0.3	1.8±0.7
4) TOTPLAN	230	508±126	9±0.3	2.0±0.9

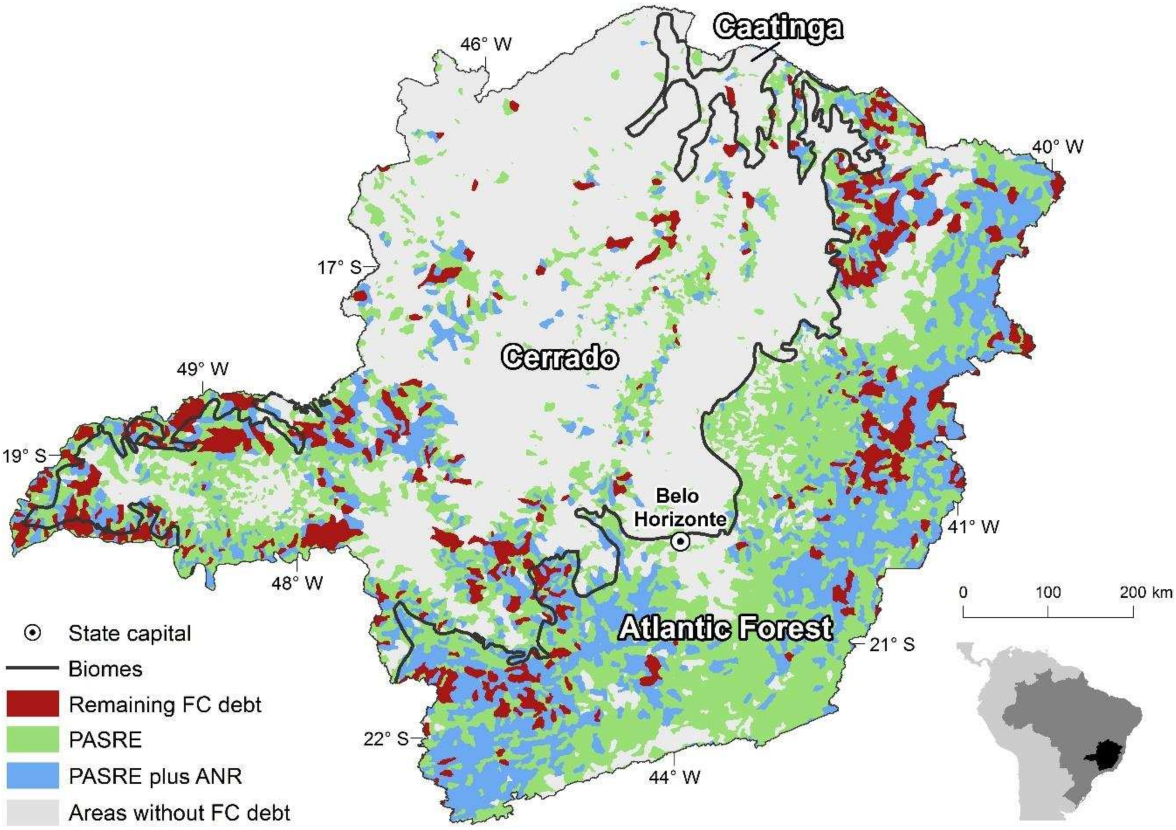

Figure 3: Solving the FC debt by employing PASRE and ANR. The remaining FC debt would require PARPLAN and TOTPLAN methods.

Fully solving of the FC debt of Minas Gerais would sequester 345±86 $MtCO_2e$ (million tons of CO_2 equivalents), but the cost per ton varies greatly (Figure 5). A price of US$ 1.1 per tCO_2e would cover the private costs where only PASRE is needed over a 20-year period. The mean carbon sequestration per hectare (220±85 tCO_2e/ha) would suffice to pay the marginal costs of fencing (0.24 thousand US$/ha).

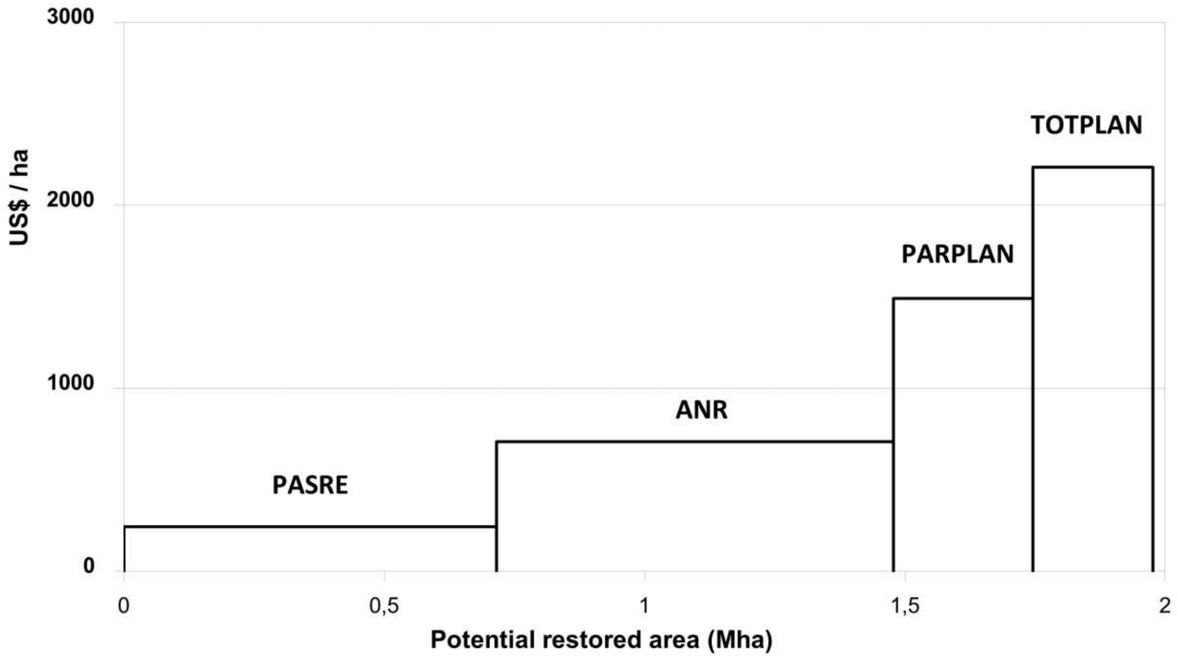

Figure 4. Marginal abatement cost curve for restoration of native vegetation**.**

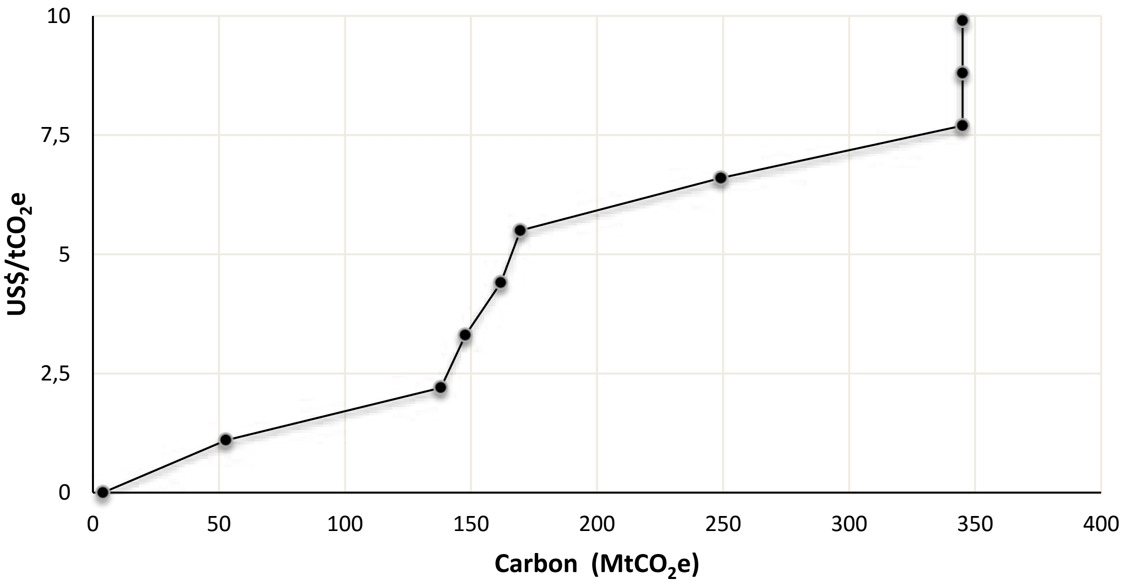

Figure 5: Marginal abatement cost curve for carbon sequestration.

The total private costs to solve the FC debt in Minas Gerais would reach US$ 1.6±0.3 billion (Table 3). Our estimates of public costs for implementing the PRA would total US$ 90 million (Table 3). Moreover, our results indicate that land-use opportunity costs present a great barrier to adopt compliance in the absence of law enforcement. The sum of private and public costs totals US$ 1.7±0.3 billion. But, when the opportunity costs of compliance are included the total costs shoot up to US$ 4.8±1.5 billion.

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).

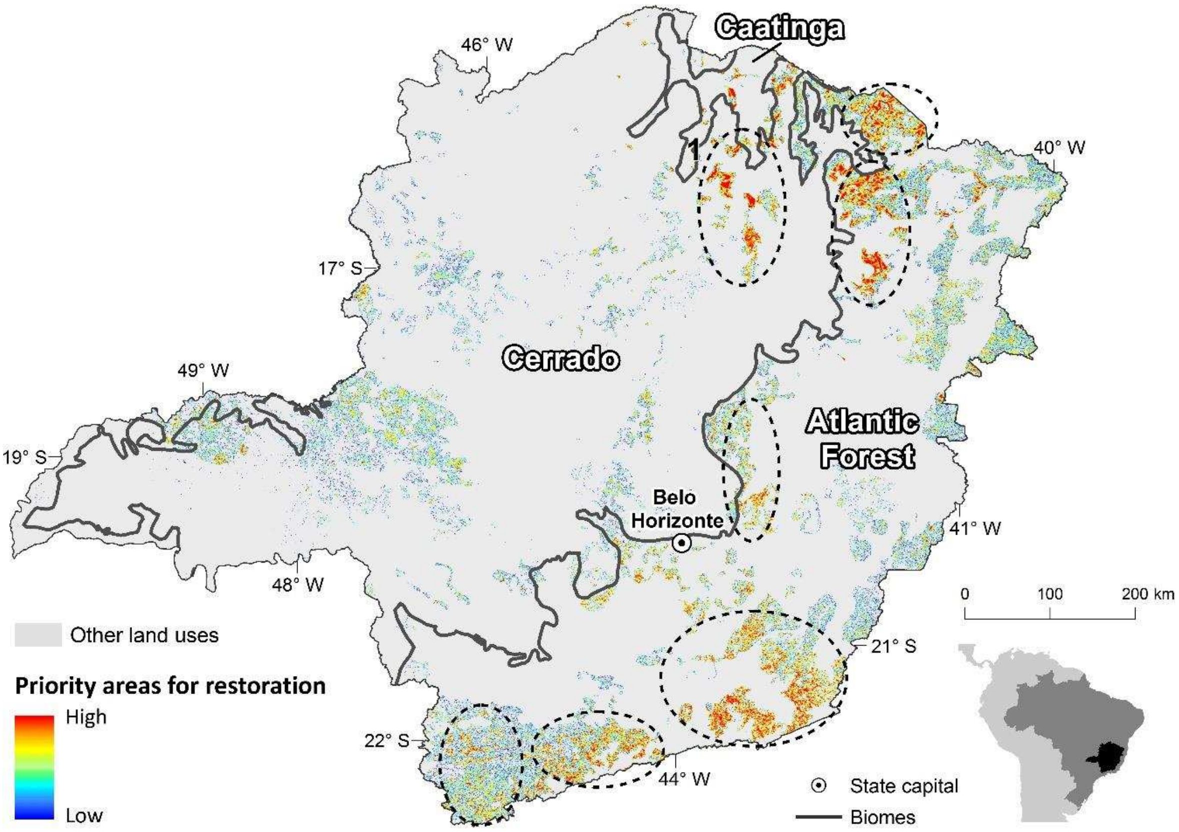

Figure 6: Priority areas of the FC debt in Minas Gerais for large-scale restoration projects aimed to enhance ecosystem services, including carbon sequestration,

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. Rather than large-scale simulation vegetation models (Snell *et al* 2014, Keane *et al* 2015), our fine spatial resolution approach enables the assessment of landscape features on the local natural regeneration potential. As a result, our study confirms the findings of Martins *et al* (2014a) that large areas with high to medium potential for passive restoration occur at the landscape level. The enormous area to be restore and its costs will require different degrees of intervention combining passive and active restoration methods in order to take advantage of the natural regeneration potential. Only planting seedlings, the most widely and often costly restoration approach used until now (Brancalion *et al* 2016), may not be feasible to achieve the FC compliance in Minas Gerais. Therefore, our results reinforce the role of natural regeneration in significantly reducing the cost of large-scale restoration (Chazdon and Guariguata 2016). Policies aimed at solving the FC debt (2 Mha) under the PLANAVEG should therefore prioritize areas with high natural regeneration potential (1.5 Mha) across the State. In this regard, our study serves as guide to point out the priority areas for carrying out large-scale restoration projects together with their potential environmental benefits.

There is a need, however, to develop an appropriate legal framework for the PRA 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). Restoration policies should also encourage landowners, who are above compliance but have low opportunity costs and lands with high potential for natural regeneration, to restore part of their lands to offset through the CRA market (Soares-Filho *et al* 2106) the FC debt of areas with high land-use opportunity costs or that require costly active restoration. In addition, 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-year 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 $MtCO_2e$.

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 refer to the challenges related to large-scale governance (Metzger and Brancalion 2013) and the lack of long-term studies for assessing costs and ecological benefits of restoration (Wheeler *et al* 2016). Furthermore, we need to understand to what extent landowners are willing to internalize the substantial opportunity cost related to forest restoration. Individual farmers will only restore their FC debt if the costs incurred by staying incompliant in the form of market restrictions or fines are higher than their land-use opportunity costs.

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. This is important, especially in the case of the Rio Doce water basin, for example, where heavy investments are needed to mitigate the large impacts caused by the rupture of Samarco´s tailings dam (Fernandes *et al* 2016).

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 – PRA. And if we want to promote restoration beyond the FC compliance, these policies should contemplate programs for payments for ecosystem services (PES), such as the State’s program Bolsa Verde. Regarding the latter, the extended market of CRA, named XCRA (Soares-Filho *et al* 2016), offers a unique opportunity to disseminate PES programs across Brazil.

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CAPÍTULO 2

BOUNDARY WORK IN CLIMATE POLICY MAKING IN BRAZIL: REFLECTIONS FROM THE FRONTLINES OF THE SCIENCE-POLICY INTERFACE

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ABSTRACT

Despite challenges to the authority and legitimacy of science as a neutral representation of the world, expert advisors are playing an increasingly central role in environmental policy-making in both the Global North and South. This article explores the science-policy interface, based on the experience of the main author as a scientist and policy-maker at FEAM, a state-level environmental agency in Brazil. Contributing to the literature on boundary objects and organizations, the article details the practices necessary to manage the relationship between political and scientific norms in the development of the regional Climate and Energy Plan (CEP) for the state of Minas Gerais. To sustain the role of FEAM as a boundary organization mediating between political and scientific demands, a team of scientists and policy-makers had to perform different types of boundary work in a closely connected manner. It was necessary to actively frame climate change as an economic problem, and structure its solution in terms of mitigation mechanisms. Responding to changes in the national and international political context, FEAM reframed climate change from mitigation into largely an adaptation issue that could lead to win-win solutions as to attain saliency and avoid insurmountable political obstacles for its approval. Based on this experience, the article argues that the performance of boundary objects and organizations in the science policy interface not only requires an ability to bring 'truth to power' but to also the capacity to sense, anticipate and avoid political obstacles. For this reason, even though boundary organizations provide a breeding ground for institutional learning it is an unsuitable location for scientific or political revolutions.

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1. Introduction

For millennia scholars have claimed to have not only a privileged epistemological viewpoint of the world but also a duty to promote the common good by 'telling [the] truth to power'. The dream of a Positivist State as determined by the Philosopher kings came close to fruition during the mid 20th century as a consequence of the central role of the natural sciences (and in particular physics) in the Great Wars. Based on this vision, diferente scholars have highlighted the importance of creating policies driven by sound scientific knowledge, in isolation from everyday politics (Esty, 2004). However, in the last few decades, the authority of science has been called into question by citizens wary of the risks brought about by new technologies and scientific discoveries (Beck, 1992) as well as the emergence of wicked problems which solutions go beyond traditional scientific approaches (Funtowicz and Ravetz, 1993). Thus, the epistemological privilege of science in providing unquestionable answers has been challenged, since it is often seen more as a source of anxiety and environmental catastrophe than as a one-way ticket to Utopia (Guston and Keniston, 1994).

Climate change is testimony to the central and yet contentious role of science in modern governments. While the latter still look towards science for universal answers, expert advice not always is translated into policy actions. In some places, such as the United States, the hesitant character of climate policy has emerged partially as a result of more or less concerted efforts to question the existence of anthropogenic climate change (Demeritt, 2006; Oreskes and Conway, 2011). However, even in regions such as the European Union and Brazil, where challenges to climate science are less prevalent, there is considerable political and scientific disagreement about how to establish a balance between environmental, economic and social objectives (Backstrand and Lovbrand, 2006; Van der Hoff et al., 2015; Markard et al., 2012).

Scholars from science and technology studies as well as those from political science have recognized the complexities of the relationship between science and policy. For example, this body of research has detailed the role of scientific advisors in policymaking (Jasanoff, 1990), the presentation and negotiation of scientific uncertainty (Shackley and Wynne, 1996) and the instrumentalization of scientific data by politicians to manage political crises (Rajão and Georgiadou, 2014). Nevertheless, while our theoretical understanding has improved substantially in the last two decades, there are very few accounts and reflections in the literature from within the science-policy interface. More importantly, policy-makers and science advisors find it difficult to obtain pragmatic guidance from this body of literature as it is often more concerned with theoretical debates than public engagement (Sutherland et al., 2012). This article aims to contribute to this literature detailing some of the practices that were necessary to manage the relationship between political and scientific norms in the development of the regional Climate and Energy Plan (CEP) for the state of Minas Gerais. To this end, the article is an account of the first author's participant observation over a period of four years as the climate policy team leader in the State of Minas Gerais[1]. The article is based on personal notes and informal interviews with the different actors involved in the policy-making process. It shows how the author and his team had to perform hybrid political and scientific practices in order to: establish CEP as a boundary object adopted by different groups both inside and outside the government and sustain the role of FEAM as a boundary organization mediating between political and scientific demands. In the next section there is a brief summary of science-policy interaction literature, addressing the core concepts of boundary objects, organizations and hybrid practices. This is followed by the empirical section and a discussion of the research findings.

2. Boundary organizations in the science-policy interface

In the last three decades, the field of science and technology studies has started to develop a rich theoretical tradition exploring how science and policy emerge from the interaction of social worlds. To address this matter, the starting point of Star and Griesemer (1989) was an emerging scholarship, later known as actor-network theory. The proponents of this theory suggested that strong scientific statements emerge from the ability of some actors to enlist human and non-human actors to join their networks (e.g. a scientist encouraging a colleague from another field to agree to his theory). This is done when actors translate and inscribe their own interests in other actors (e.g. by convincing the colleague that the results of her ongoing research are coherent with his theory). In this way, other actors start acting on the behalf of the former (e.g. giving support and citing his scientific theory, establishing it as a scientific fact). Indeed, it is possible to claim that this (arguably) Machiavellian enables different forms of coercion. This includes the establishment of obligatory points of passage and the mobilization of networks via immutable mobiles such as research funding, laboratory instruments and quantitative data (Latour and Woolgar, 1979; Callon, 1986; Latour, 1987).

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[1] Even though the article was written in collaboration with the co-authors, it is presented from the point of view of the main author.

Star and Griesemer (1989) have observed a different situation in the historical material concerning the creation of a scientific museum in California. In contrast to the emergence of a pyramidal network centred on a set of actors, they have found a situation where many actors largely operate independently. Furthermore, rather than finding a strict alignment between these actors, they observed the emergence of a loose form of coherence between relatively self-contained social words, each one with their own local work arrangements and obligatory passage points. It was by trying to understand what enabled the creation of coherence (rather than alignment) and cooperation (in contrast to coercion and hierarchical coordination) that Star and Griesemer (1989) coined the concept of boundary object (Sapsed and Salter, 2004: 1519). In particular, this notion refers to artifacts and concepts (e.g. maps, notebooks, specimens) that serve as the basis for cooperation by being plastic enough to be adapted and used locally while still maintaining a common identity across boundaries. Since then, a wide range of studies have drawn upon this theoretical tradition to explain how concepts, maps and computer models (including climate simulations) have facilitated cooperation between scientists and policy-makers (Shackley and Wynne, 1996; Carton and Thissen, 2009; Harvey, 2009; Rajão and Hayes, 2012). Later, Guston (1999) put forward the idea that not only objects but also entire organizations could take the role of mediators between Science and policy by satisfying the social requirements of both domains. Here, in addition to the ability to create boundary objects, an ideal boundary organization should involve scientists and policy communities in a coordinated way and should have lines of accountability on both sides (Guston, 2001). In some cases, these organizations go even further by creating hybrid management practices with the aim of negotiating incommensurable differences between these domains (Miller, 2001). As stressed by White et al. (2010), boundary organizations:

> ...internalize the differences of actors and institutions on both sides of the boundary, negotiate across them to develop decision-making options... providing a space for the creation and use of boundary objects, which are hybrid constructs that integrate elements from scientific and political worlds to facilitate the negotiation and exchange of multiple types of knowledge and action (White et al., 2010: 221).

Therefore, a boundary organization potentially facilitates participation across boundaries, expanding the opportunities and incentives for joint knowledge production when dealing with complex social and environmental issues (Miller, 2001; Franks, 2010; Boezeman et al., 2013). Once successfully established, boundary organizations can help stakeholders to negotiate their different priorities, frames and activities around the pressing need to share important information (Lee et al., 2014) and to agree upon common political goals (Guston, 1999).

Structural factors, such as legally established jurisdictions (Miller, 2001), research funding (Rip, 2001) and specific political-cultural contexts (Hoppe, 2010) are important for the establishment of boundary organizations. However, in addition to these factors, more recently some studies have shown that specific types of boundary work are key for the emergence and maintenance of institutions as boundary organizations (Cash et al., 2002, 2003; Jasanoff, 2004; Kemp and Rotmans, 2009). These include the balancing of credibility, legitimacy and saliency (Cash et al., 2003) and the process of problem framing and structuring (Hoppe and Wesselink, 2014). The emphasis of this literature on boundary organizations as the outcome of boundary work rather than stable entities has provided important insights into the relationship between politics and science in climate governance. However, only a few empirical studies detail the work done by the actors at the forefront of the science-policy interface (Hoppe, 2008; White et al., 2010). Most studies rely only on textual sources and interviews. As a consequence the current literature tends to understate the uncertainties, conflicts, paradoxes and dilemmas that the members of boundary organizations have to face in order to successfully mediate between social worlds.

The next section provides an account of the first author’s experience as both a policy-maker and scientist at FEAM (the State Environmental Foundation), a boundary organization from the government of Minas Gerais. Here, particular focus will be given to the boundary work the author carried out with his team in order to perform FEAM as an effective boundary organization and to successfully create the Climate and Energy Plan (CEP) as a boundary object that would be adopted by the different parts of the government. For this purpose, the article will draw inspiration from and expand on the approach provided by Hoppe and Wesselink (2014) to emphasize boundary work mainly as a problem structuring and solving process. In particular, emphasis will be given to the role of three interrelated boundary work practices in creating CEP: 1) problem framing which establishes the goals of the policy by delineating what the problem includes and what the underlying cause is (see also Stone,1989); 2) problem structuring and knowledge selection which reduces normative ambiguities and uncertainties by proposing solutions; and 3) the creation of intermediary boundary objects such as simulation models and economic studies.

3. Climate policy-making in Minas Gerais

Minas Gerais is one of the 26 states of Brazil. It ranks as the second most populous state and the third largest according to gross domestic product (GDP). Located in the south-east of the country, the state has an area of 586,528 square kilometers (approximately the size of France) and is the fourth most extensive state in Brazil. The service sector is the largest component of its GDP at 62%, but activities with large environmental impacts, such as the industrial sector (including mining) and agriculture represent 29% and 9% of the economy respectively.[2] The creation of a state-level environmental agency dates back to the 1970s with the establishment of the Environmental Policy Council (COPAM). In line with the desire of the military dictatorship at the time to establish a technocratic government and enhance the rationalization of public service (Diniz, 1981), the state also created subsidiary technical bodies, such as the Technological Foundation Center of Minas Gerais (CETEC) and the Superintendence of Environment (SMA) to inform policy-making. An ex-director of SMA, who would later become FEAM’s President, remarked that ‘there was a clear separation between political power and technical knowledge’ (Pereira, 2010: 46). Despite the attempt to separate science from politics, the same person also remarked that the ‘pluralism of [political] representations . . . induced the development of the art of negotiating and managing conflicts’ (ibid: 42–46).

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[2] Available at: http://www.fjp.mg.gov.br/index.php/produtos-e-servicos1/2745- produto-interno-bruto-de-minas-gerais-pib-2.

This institutional arrangement evolved into a system of environmental bodies that includes the Secretary of Environment and Sustainable Development (SEMAD), the State Institute of Forests (IEF), the Water Management Institute of Minas Gerais (IGAM) and the State Environmental Foundation of Minas Gerais (FEAM). In addition to focusing on the brown environmental agenda relating to urbanization and industrialization, FEAM incorporated the technical staff from the now extinct CETEC and SMA in order to provide scientific-technical studies, territorial environmental assessments and planning instruments to state-level environmental policies. To this end, FEAM has invested heavily in staff training, focusing on management tools, environmental governance and economic mechanisms. Many civil servants have participated in training courses, studying for master's degrees and doctorates, this being widely supported institutionally. FEAM staff has also published several studies in national and international journals, addressing waste management, renewable energy, sustainability indicators and other environmental issues relating to climate change and environmental governance in the state (FEAM, 2012; Xavier et al., 2013; Bassi et al., 2014). Thus, FEAM, which already has an institutional culture as a 'technical institution', has fostered the 'scientification of politics' by increasing the use of scientific knowledge in the formulation of environmental policies (Weingart, 1999; Wesselink et al., 2013). Hence, it is possible to say that the history and mission of FEAM are closely related to the agencies described in the literature as boundary organizations (Guston, 1999; Miller, 2001; Hoppe and Wesselink, 2014).

The first author of this article joined FEAM in 2009 as a career civil servant during the last year of a Masters Degree in Environmental Modelling, and started a PhD in Applied Meteorology in 2012 with the support of FEAM. Because of the expertise acquired as an environmental analyst and researcher, the author was appointed manager of Climate Change and Energy in 2011 in a group under the Research and Development Directorate. The group is formed by seven environmental experts from FEAM and ad hoc scientific advisors from a variety of institutions. Building on the work started at FEAM in 2007 the climate team developed and discussed greenhouse gas emissions and policy scenarios with groups both inside and outside the state government. From this process it was finalized in the early 2015 Minas Gerais' Climate and Energy Plan (CEP) for the years 2020 and 2030. CEP is a transversal policy involving sectorial actions, targets and indicators not only for the state environmental agencies (SEMAD, IEF, IGAM, FEAM) but also for the Secretaries of Agriculture (SEAPA), Economic Development (SEDE), Planning and Management (SEPLAG), Science & Technology (SECTES), Finance (SEF), Regional and Urban Development (SEDRU), Transportation (SETOP) and other government institutions (FEAM, 2015). The plan has also been adopted by the State Integrated Development Plan (PMDI), a long-term plan, complemented by the Mid-Term Budget Plan, a four-year budget plan, and the Annual State Budget.[3] It is important to note that the policy-making process of CEP continued despite the political changes in the state government between 2007 and 2015 when there were four different governors and two opposing political coalitions in power. It is therefore possible to argue that CEP became a boundary object shared by different sectors and political groups from Minas Gerais state government.

For an outsider the development of CEP could easily be interpreted as the outcome of a technical exercise involving the application of scientific knowledge to policy-making. However, an examination from within the science-policy interface reveals a much more complex picture. Below is a description of the boundary work required to perform CEP as a boundary object and FEAM as a boundary organization drawing upon the conceptual framework proposed by Hoppe and Wesselink (2014). The case study is divided in two periods based on the prevailing way FEAM's climate team structured the problem of climate change in the context of the development of CEP.

3.1. Mitigating climate-related economic losses (2007–2013)

The discussion inside the government of Minas Gerais concerning the need for the creation of a state-level policy on climate change started in 2007 and was further intensified in 2009. In this period climate change emerged as a key political issue as countries were negotiating a new agreement in the 15th conference of the parties (COP) in Copenhagen which could have led to the creation of a strong regime for the control of greenhouse gas (GHG) emissions. The international community did

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[3] Available at http://www.planejamento.mg.gov.br/planejamento-e-orcamento/plano-plurianual-de-acao-governamental/ppag-2012-2015.

not manage to reach consensus, but in the aftermath of the meeting 15 developed countries alongside the European Union submitted quantified economy-wide emissions targets for 2020, while 39 developing countries proposed nationally appropriated mitigation actions. In the specific case of Brazil, the Federal Government proposed reducing GHG emissions by 36.1 to 38.9% by 2020 in relation to a projected business as usual scenario.

FEAM considered it critical to understand the implications of the national climate change policy to the state-level and to consider more ambitious policy options. Given the scientific training of the team, it was clear to them that state governments should also contribute to tackle climate change. However, in order to convince the different sectors of the government of the relevance of climate change policy in the specific context of Minas Gerais, FEAM understood that this issue had to be framed not only as an environmental problem but also as an economic one. To this end, in 2011 an assessment was conducted to estimate the impact on the state economy of changes in temperatures and rainfall according to the scenarios from the Intergovernmental Panel on Climate Change (IPCC). The study was carried out with the assistance of the University of São Paulo as part of a broader study to estimate the economic impact of climate change in Brazil, this being inspired by the Stern report from the British government which was published in 2006 (FEAM, 2011; PBMC, 2013; Stern, 2006). The findings of the study were published in the weeks preceding the United Nations Conference on Sustainable Development, Rio+20, and as such attracted considerable media attention. Three years later, its main result was included in the second paragraph of the introduction of CEP to set the tone for the plan:

> It is estimated, in a conservative way, that if nothing is done, the costs of the impacts from climate change, for the state economy could reach in the next decades (2015) around R$ 450 billion (without considering the impact from extreme weather events). (Bold in the original, FEAM, 2015: 9)

Having framed climate change as an economic threat, the team started to discuss Minas Gerais mitigation targets and implementation actions. However, the structuring of climate change as a mitigation problem has proven to be much more controversial than the team had first anticipated. Initially FEAM envisaged the implementation at state and national levels of a strong mitigation policy based on some sort of cap and trade market mechanism. To proceed in this direction, it planned the creation of a detailed, firm-level registry of greenhouse gas emissions in order to establish the responsibility of each economic agent and to obtain a stable influx of financial resources to reward reductions. The first step in this direction was taken in 2009 with the creation of a voluntary registry and the involvement of some of the state's largest companies. Later, based on the experience of Minas Gerais and two other states with similar registries (Rio de Janeiro and São Paulo), the Federal Government organized a working group to provide the technical basis for a national registry to provide the basis for a domestic carbon market. However, the initiative was curbed by influential sectors from the federal government and the creation of a national registry was sidelined. At the same time it was also becoming clear that the possibility of obtaining financial support for state-level mitigation actions from federal or international sources would be extremely unlikely since initiatives such as REDD+ were centralized at the national level (Van der Hoff et al., 2015). With the lack of external financial resources for mitigation, it would have been necessary to either mobilize the state budget or regulate economic activities with restrictive command-and control policies. However, these options would pose a direct challenge to the development imperative of the most influential sectors of the state government and as such were considered politically unviable by the team.

Given the struggle to structure the solution for climate change in terms of ambitious regional mitigation plans, the climate team felt the need to develop a proposal that would neither rely on strong political support nor face insurmountable opposition inside or outside the state government. Firstly, it was established within CEP that Minas Gerais state would need to support at least its own share of the national mitigation compromise set out by the federal government in Copenhagen. Since the mitigation plan of the federal government relies mostly on reducing deforestation levels in the Amazon biome (i.e. Minas Gerais hosts the Cerrado and Atlantic Forest biomes), the state would need to reduce its emissions by only 7–9% in order contribute to the national target. In the light of the lack of local political support for a more ambitious target and the restricted governance in the energy sector (a federal government attribution), FEAM’s climate team had to propose a modest alternative scenario that adds only 12.38% to the federal mitigation target.

While the low mitigation target rendered CEP politically viable, it raised some concerns within the team regarding the environmental benefit to be obtained from CEP. One of the key problems with the national plan was the assumption of a business as usual (BAU) scenario based on a gross domestic product (GDP) growth of 5% — a rate well above the country’s historic average (Federal Decree 7390/2010). Hence, the mitigation target could be met without additional efforts. In order to avoid this kind of criticism from environmentalists and scientists and to ensure that CEP would have more concrete mitigation effects, a different BAU scenario methodology was used, utilizing conservative GDP projections for the state economic activity and including carbon intensity targets, namely, emissions per capita or per R$ produced. Despite not being completely aligned with the Brazilian official position in international negotiations, the carbon intensity approach shared the premise of compatibility between economic growth and concrete greenhouse gas emissions reductions, and as such was expected to be adopted more easily by other sectors of the government.

3.2. Adapting to climate change via the green economy (2013–2015)

Despite FEAM’s effort to propose acceptable mitigation targets, the initial emphasis of Minas Gerais’s climate policy on mitigation was challenged. As the consultation process began, diferente groups inside the government questioned the role of state-level mitigation actions given the uncertainty relating to the actions of other national and even sub-national entities. For instance, it was indicated in meetings with the Environmental Policy Council (COPAM) that even if Minas Gerais were able to radically reduce its GHG emissions through an ambitious mitigation plan, it would still suffer the negative effects of climate change if emission levels remained high at a global level. As mentioned by a councillor of COPAM, ‘the State of Minas Gerais cannot pay the bill for the historical emissions of developed countries. Following the principle of common but differentiated responsibilities we should receive money to fight climate change’. This perspective was reinforced by the pessimism that followed the collapse of the negotiations during the COP15 in Copenhagen. As an influential Brazilian policy-maker at federal level and IPCC scientists made clear in an interview in 2012, ‘many people [politicians and scientists] have thrown in the towel and do not believe that there is any chance of reducing emissions anymore’.

In response to the difficulties relating to furthering the mitigation agenda, the team started to reframe climate change at state-level mainly as an adaptation issue. In practice, this meant reverting the direction of climate policy. Instead of considering ways to act locally to mitigate a global problem, the problem developed into a matter of how to adapt locally to an avoidable global change. Consequently, two additions to CEP were made in order to structure adaptation into a solvable public problem: the definition of adaptation as both a threat and an opportunity to the energy sector, and the translation of this agenda to the needs and concerns of the different sectors and regions of Minas Gerais. To achieve this redefinition during the second phase of the creation of CEP, the team started to collaborate more closely with a group of European consultants who specialized in adaptation and regional climate policies. These were supported by a collaboration agreement with the French Region of Nord-Pas de Calais and the French Agency for Environment and Energy Management (ADEME). This agreement was important for the policy-making process during a period of constant and sometimes substantial political change in the state government. Most importantly, this collaboration led to the incorporation into CEP of the concept of “green economy”: a problem structuring approach which has gained considerable space in climate policy in the European Union. The key assumption behind this concept is that climate change is not only an environmental crisis but also an economic opportunity for business and governments willing to adapt to this new scenario. The following excerpt from an influential report from the United Nations Environmental Program (UNEP) captures this position:

> Perhaps the most prevalent myth is that there is an inescapable trade-off between environmental sustainability and economic progress. There is now substantial evidence that the greening of economies neither inhibits wealth creation nor employment opportunities. To the contrary, many green sectors provide significant opportunities for investment, growth and jobs. For this to occur, however, new enabling conditions are required to promote such investments in the transition to a green economy, which in turn calls for urgent action by policy-makers (UNEP, 2011: 16).

The team was well aware of the limitations and some of the criticism relating to the green economy (Bina and La Camera, 2011; Victor and Jackson, 2012; Kosoy et al., 2012). However, the team agreed that it would be important to adopt the concept in order to prevent hard political opposition from key stakeholders regarding the adoption of climate change measures with possible negative effects on economic growth. In particular, following the same path set out by the European Union in its climate policy, CEP sought to emphasize the possible role of Minas Gerais's energy sector in the green economy. As a starting point for that, FEAM, in collaboration with international consultants (including one of the co-authors of the UNEP report cited above) developed a diagnosis and a simulation model of energy production and consumption, contrasting the business as usual (BAU) with a reduced carbon intensity scenario (see Xavier et al., 2013). The study argued that the energy sector was already vulnerable from both an economic and environmental point of view. On the economic side, it highlighted how the state today imports 57% of its energy demands (mostly fossil fuels) from outside its territory, and as such, the regional economy is likely to suffer with price fluctuations and other economic factors. On the environmental side, even though 30% of the energy produced in the state comes from hydropower, this energy source has almost been exploited to its maximum in the state and is highly vulnerable to droughts, such as the ones the state is currently experiencing. Due to the lack of precipitation and investment in the sector, the use of power plants based on fossil fuels increased considerably in recent years. Thus, since the study examines what is likely to take place until 2030 (the BAU scenario), it suggests that the inaction of the state government may lead to both an economic crisis (since production will not meet demand) as well as environmental difficulties (as GHG will keep increasing).

However, rather than considering the energy crisis as only a threat (as in the mitigation framing), based on the concept of the green economy CEP emphasized that this situation also provides important opportunities for economic growth and job generation. In particular, and as part of this study, an attempt has been made to structure the solution to the climate-energy problem as a win-win prospect. Firstly, the plan argued that there was considerable scope for improving energy efficiency in different sectors. For instance, the plan proposed that with improvements in house appliances (illumination, heating, and air-conditioning) and in the ceramics industry, it is possible to reduce energy demand by 53% and 43%, respectively. This would lead to multiple benefits since lower energy consumption could avoid an energy crisis, reduce energy bills and mitigate GHG emissions. Secondly, the study also emphasized the potential for energy production from renewable sources (FEAM, 2015: 14) and presented a low carbon intensity scenario in which the state would not only be able to meet its demand but could also become an exporter of energy, bringing in this way important environmental and economic benefits (see Fig. 1; see also Xavier et al., 2013).

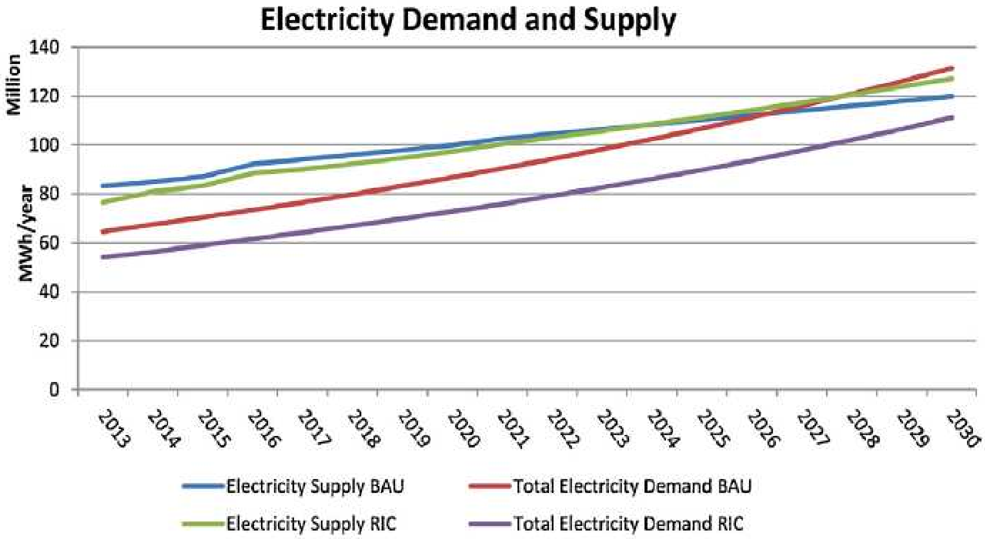

Fig. 1. Energy demand and supply from the state of Minas Gerais in a business as usual (BAU) and carbon intensity (RIC) scenario.

Table 1. Three main boundary work practices undertaken by Feam in order to create the Minas Gerais State Energy and Climate Change Plan (CEP) (adapted from Hoppe and Wesselink, 2014

Boundary work and objects	**2007-2013**	**2013-2015**
Problem Framing (goals/ends)	- Climate change mitigation in order to avoid economic losses from gradual changes and extreme weather events	- Climate change adaptation in order to reduce regional climate vulnerability and risks from energy/water shortage

Problem Structuring and knowledge selection (instruments/ means)	• GHG registry • Economic incentives instead of command and control	•	• Adaptation as an environmental problem with economic solution • Green growth and climate adaptation as win-win solutions
Intermediary objects	• Model of economic impacts from climate change (USP)	•	• PCET methodology (French collaboration • Energy consumption/production diagnosis and simulation (French collaboration • Land-use simulation (UFMG)

Another important change to CEP came about with a growing emphasis on the 'territorialization' of FEAM's policy-making effort brought by the French collaboration. As was already evident in the study conducted by the team in collaboration with the University of São Paulo in 2011, climate change will affect the various parts of the state very differently. While the south, center and west (i.e. Triângulo Mineiro) of the state present a relatively low level of vulnerability, regions that are already prone to droughts such as the North and Jequitinhonha/Mucuri valleys are likely to have severe economic losses. At the same time, every region of the state has its own set of key economic sectors and political interest groups.

In order to deal with this diversity, the climate team sought help from the French government to develop a Territorial Climate Energy Plan (PCET), a policy-making tool that aims to foster the green economy with a particular emphasis on participatory local development initiatives. Drawing upon the French experience this approach recognized climate change largely as a regional problem and as an economic opportunity to simultaneously boost economic growth and reduce carbon emissions. With the regional workshops, the main purpose was to stir social mobilization in the territory and thereby to foster a type of climate change governance that is able to recognize different social perspectives and needs. Taking into account the decentralization strategy of the workshops, climate adaptation was treated as a local issue, in line with the challenges previously identified for each region. In terms of the number of institutions and the representativeness of the regions, the actors involved in the participatory process included the following sectors: agriculture (7 institutions), energy (4 institutions), industry (8 institutions), environment (9 institutions) sanitation (2 institutions), transportation (1 institution), education (2 institutions), health (2 institutions) and cross-sectorial organizations (23 institutions).

Every workshop had a moderator who actively participated in the generation of scientific knowledge (diagnosis and scenarios), this being recognized in both the scientific and political worlds. All the workshops aimed to mobilize social groups, exchange ideas and overcome political barriers. However, during the process, it became apparent that some stakeholders were uncomfortable with quantitative projections and pre-established targets defined in the problem structuring phase. Therefore, the team changed its strategy emphasizing CEP as a cross-sectorial planning and management tool. In addition, the team adjusted the formal presentation of CEP and its engagement strategies by region in order to reframe climate change and its related adaptation strategies to their specific circumstances. In this way the team attempt to act as scientists informing lay stakeholders and as mediators responsible for negotiating priorities and ‘world views’ between regional actors. As argued by Hegger et al. (2012), the team acted as ‘process organizers that structure knowledge providing technical expertise; supply knowledge about data sources and their use; and afford access to international networks’.

For instance, in the regions where the agriculture, forestry and other land use (AFOLU) sector is prevalent it is crucial to reduce GHG emissions from deforestation. In order to achieve this result, the traditional approach includes command and control actions by environmental agencies. However, in the engagement process with the agricultural sector, more focus was placed on the potential of GHG removals in terms of improving farming technologies. To evaluate the potential of this alternative the team used a simulation platform developed by the Federal University of Minas Gerais to model changes in land use, carbon dioxide emissions and environmental impacts (Soares-Filho et al., 2013). One of the key findings of the study was that it would be possible to avoid deforestation by slightly increasing the productivity of cattle ranching and freeing new pasture areas for agricultural lands. Additionally, the study showed that it would be possible to reduce the vulnerability of agricultural areas with the expansion of irrigation plots. The contributions from the participatory process were evaluated by FEAM and the suggestions regarded as having social relevance and economic benefit were included in CEP. In this way an attempt was made to structure climate change as an adaptation problem with win-win solutions able to cater for both environmental and economic demands.

4. Discussion and conclusion

From the account presented above, it is possible to observe that the Minas Gerais Climate and Energy Plan (CEP) did not emerge from the mere translation of scientific knowledge about climate change into policy, as often suggested by natural scientists and economists (Esty, 2004). CEP was also not the outcome of a purely political process where different views clashed and compromises were made. Instead, the creation of CEP was the result of a complex interaction between the demands, restrictions, knowledge forms and actors from the spheres of politics and science.

In the literature it has already been possible to see the central role of boundary organizations such as FEAM in facilitating the dialogue in the science/policy interface (Guston, 2001; Miller, 2001). Similarly, it is clear that objects such as CEP, which are sufficiently flexible to have both a common use and specific usages across boundaries, are crucial for enabling cooperation between the different social words of science, environmental regulation, development policies and business interests (Start and Griesemer, 1989; White et al., 2010). In expanding on this literature, this article has shown that the emergence of FEAM as a boundary organization and of CEP as a boundary object took place because of a set of boundary work practices which were carried out by FEAM's climate team in an adaptive and contextual manner.

The theoretical formulation of Hoppe (2010) on boundary work as a problem framing and structuring process has proved to be useful to understand the creation of CEP (Hoppe, 2010; Hoppe and Wesselink, 2014). Hence, by critically examining this regional climate policy-making experience, it was possible to observe how the framing of climate change as a public problem has changed substantially over the years (see Table 1). From the start, the team was faced with the challenge of framing climate change not only as an environmental problem (which would not attract sufficient regional political support per se) but also as an economic issue.

However, while it was framed as being avoidable through mitigation, the problem was later reframed as an unavoidable problem requiring a local adaptation strategy. Moreover, this localization of climate change was also reinforced by structuring this issue as a local rather than national problem. Further, it was possible to observe a very close coupling between problem framing (ends) and structuring (means). Here, as the solutions envisaged for mitigation (e.g. GHG registry, carbon market, REDD+, etc.) became increasingly distant, it was also necessary to reconsider the problem itself. In this context, the reframing of climate change as a sub-national adaptation problem made the continuation of the creation of CEP possible by opening new problem structuring landscapes. This was achieved by considering the plan as a means to foster the green economy especially in the energy and AFOLU sectors.

The concepts derived from the green economy framework (UNEP, 2011) facilitated a climate change framing that was aligned to the strategic planning of the Minas Gerais state. Here climate change was perceived more as an opportunity to foster a low carbon economy than an insurmountable crisis. In addition, this approach anticipated conflicts related to the trade-offs between climate change and economic policies, so reducing the resistance in particular from the agricultural and industrial sectors. Clearly, this framework avoided hard (and much needed) political discussion about the global economic model and the urgency of adopting stronger environmental policies. However, as stated by Hegger et al. (2012), ‘only if actors have good reasons to expect the participation to result in “win–win” situations, [will] their participation [. . .] be advisable’.

For the creation of CEP it was also necessary to develop diferente studies that played the role of intermediary boundary objects (see Table 1). The economic impact model, PCET methodology, land-use and energy consumption/production diagnosis and simulation developed in the context of CEP all had a point in common:

to look at the future consequences of climate change in relation to present policy-making efforts. To accomplish this, it was necessary to accommodate two sets of very different demands. On the one hand, these simulation models needed to be within the scientific sphere in order to portray a likely future in a legitimate way. Moreover, while FEAM’s own team of civil servants has scientific training, it was important that these studies were developed in collaboration with prestigious research groups in Brazil and abroad, leading in some cases to scientific publications. On the other hand, particular attention had to be given to how these scenarios were constructed and how the results were communicated. The purpose of this was to ensure the relevance of the scenarios to sectors inside and outside the government. This implied a simplification or a translation of the results to different audiences. Most importantly, it also meant that the scenarios which were not politically viable had to be eliminated from the start. Examples of these are radical cuts in absolute emissions or the creation of heavy carbon taxes. Thus, it is possible to say that these simulations acted as intermediary boundary objects because they were actively and consciously shaped by the team to take that role.

In conclusion, it is possible to reflect not only on the privilege of boundary organizations as legitimate participants of both the policy and the scientific spheres, but also on their constraints. Boundary organizations provide a unique role for science in framing questions and evaluating the feasibility of environmental management solutions (Cutts et al., 2011). In addition, they can lead to the co-production of new expertise and contribute to climate change governance by promoting collaborative efforts (Hoppe, 2010). Such institutions can provide a place to construct, deconstruct, and reconstitute scientific and political components of boundary objects (White et al., 2010). However, boundary organizations formed by government agencies such as FEAM can lead to less ambitious policies due to the need to follow administrative protocols and government procedures, prioritize the existing legal framework and deal with the political context. It can therefore be argued that boundary organizations are not the place for scientific or political revolutions. However, they do provide a breeding ground for institutional learning and change through the cross-fertilization of concepts and agendas between the scientific and political domains. Therefore, acknowledging the limitations of boundary organizations does not take away their importance to policy-making.

Instead, this shows that the performance of boundary objects and organizations in the science-policy interface requires not only the ability to bring 'truth to power' but also the capability to anticipate and internalize the politics of scientific knowledge.

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CONCLUSÕES GERAIS

Um número impressionante de modelos destinados a apoiar a formulação de políticas climáticas e ambientais têm sido desenvolvidos. Tanto a utilização quanto a confiança na modelagem científica para busca de soluções de problemas globais complexos têm se mantido generalizada no domínio da política ambiental (Laniak et al., 2013; Kelly et al., 2013). Entretanto, como grande parte da tomada de decisão ocorre em escalas regionais e locais, há uma demanda por modelos capazes de representar as dinâmicas locais no contexto dos processos globais (Verburg et al., 2015). Consequentemente, os modelos de avaliação de políticas de mitigação das mudanças climáticas e restauração florestal em esferas subnacionais precisam lidar com um conjunto próprio de objetivos legais, econômicos e ambientais para identificação de áreas prioritárias (Vogler et al., 2015) e produção de conhecimento “politicamente relevante”.

No campo da modelagem científica, o modelo de otimização desenvolvido empregou uma combinação única de métodos para espacializar o potencial de regeneração natural da vegetação nativa no estado de Minas Gerais, o que representa um avanço na literatura (Tambosi et al., 2014; Vogler et al., 2015). O potencial de regeneração natural calculado indicou uma área com médio e alto potencial que abrange 30% da área total de pastagens, o que justifica a regulamentação de métodos de restauração de baixo custo (por exemplo, a restauração passiva) para compensação de passivos florestais no âmbito do Programa de Regularização Ambiental (PRA) estadual.

Nesse sentido, a magnitude de redução de custos pode ser explorada para viabilizar a regulamentação de políticas de restauração em larga escala em Minas Gerais. Adicionalmente, as curvas de custo estimadas e os mapas de áreas prioritárias são particularmente úteis para uma alocação mais eficiente dos recursos na fase de implementação. A priorização de áreas de baixo custo de oportunidade e alto potencial de regeneração natural na paisagem pode diminuir significativamente as barreiras econômicas para cumprimento do novo Código Florestal. Neste caso, o modelo mostra que 75% do total de passivo florestal no estado pode ser potencialmente regularizado com a adoção de métodos de restauração passiva e condução da regeneração natural. E se quisermos promover a restauração além da conformidade do Código Florestal, as políticas devem contemplar ainda programas de pagamentos por serviços ambientais (PSA), como o programa estadual Bolsa Verde (IEF, 2014). Com relação a este último, o mercado ampliado de cotas de reservas ambientais, denominado XCRA (Soares-Filho et al., 2016), oferece uma oportunidade única para disseminar programas de PSA em todo o Brasil.

Potenciais melhorias no modelo podem incluir ainda a valoração da biodiversidade (Jellinek et al., 2014), projeções climáticas para mensuração do impacto na regeneração natural e preferências econômicas por parte dos proprietários rurais. Esses aprimoramentos podem ser utilizados para a construção de uma agenda de co-produção entre cientistas e formuladores de políticas a partir de uma estratégia de modelagem participativa (Cutts et al., 2011; Malek e Boerboom, 2015). Além disso, o modelo pode ser reconfigurado para estimar o potencial de regeneração natural em todo o território nacional, uma vez que as variáveis espaciais utilizadas podem servir como dados de entrada do modelo Otimizagro (Soares-Filho et al., 2016). Todavia, para espacialização dos custos é necessário reavaliar o conjunto de métodos de restauração para os demais biomas, assim como os custos de implementação dos PRAs dos outros estados da federação (custos do governo).

Claramente, é desejável sob o ponto de vista da pesquisa, um modelo integrado com a capacidade de combinar variáveis de diferentes escalas (municipal, estadual e nacional) e domínios (social, ambiental e econômico) para representar e simular trajetórias de uso da terra e restauração florestal. No entanto, essa integração dentro de um único modelo pode não ser a estratégia mais atraente do ponto de vista da governança das políticas ambientais, tendo em vista a evolução das necessidades políticas regionais e a complexidade dos fenômenos a serem modelados (Sohl e Clagget, 2013). Dessa forma, a elaboração de modelos cada vez mais complexos e integrados não garante necessariamente a elaboração e implementação de políticas mais efetivas.

À luz das reflexões do trabalho na fronteira da ciência e política, o modelo desenvolvido tem grande potencial para prover informações “politicamente relevantes” regionalmente e, portanto, facilitar a regulamentação de políticas estaduais. Contudo, a maneira como os resultados serão selecionados e comunicados com os diferentes públicos-alvo no processo decisório poderá ter impacto direto no nível de ambição das políticas. Nesse sentido, o mapa de potencial de regeneração natural e as curvas de custo podem ser explorados como objetos de fronteira visando promover o entendimento e facilitar a negociação entre as partes interessadas (White et al., 2010). Particularmente interessante pode ser a inclusão de conceitos de economia “verde” (UNEP, 2011), apesar de suas limitações (Kosoy et al., 2012), para proposição de uma agenda de oportunidades relacionada à uma economia da restauração florestal (BenDor et al., 2015). Isto permitiria enfatizar (valorar) os benefícios em detrimento dos custos para obtenção de maior apoio político no processo decisório.

Sob a ótica da condução da agenda governamental, além de pesarem os *trade-offs* econômicos e ambientais envolvidos, as medidas governamentais deverão prever barreiras técnicas, operacionais e culturais em vista das limitações de representação de um fenômeno complexo como a restauração ecológica em paisagens antropizadas. Portanto, os formuladores de políticas devem ter em mente que estimativas resultantes de modelos de otimização subestimam barreiras sociais e mudanças de regimes.

No que tange os estudos da ciência e tecnologia, o artigo apresentado no capítulo 2, ao contribuir para a literatura de objetos e organizações de fronteira (Guston, 2001; Lee et al., 2014), mostrou que há um vasto campo a ser explorado para análise das controversas relações e lacunas na interface ciência-política. Nesse contexto, as agências ambientais podem prover um leque de oportunidades para estudos empíricos focados no uso de modelos para elaboração e implementação de políticas públicas.

De maneira geral, os resultados desta tese justificam ou mesmo podem orientar a regulamentação de políticas de restauração ecológica e trabalhos de fronteira entre formuladores de políticas e cientistas. Tanto os formuladores quanto os cientistas consideram difícil obter orientação pragmática dos estudos da ciência e tecnologia, muitas vezes mais preocupados com debates teóricos do que o engajamento público (Sutherland et al., 2012). Esta pesquisa, portanto, pode auxiliar na superação desta barreira ao endereçar simultaneamente os esforços de modelagem científica e governança de políticas ambientais no campo prático.

Por fim, e não menos importante, essa tese revela a importância de maior integração de diferentes campos da ciência e da política como a modelagem de sistemas sócio-ecológicos, os estudos sociais da ciência e tecnologia e a análise de políticas públicas tradicional (feita por formuladores de políticas) para melhor compreensão das contradições, limites e possibilidades da modelagem e governança ambiental aplicadas às políticas públicas em um território.

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MATERIAL SUPLEMENTAR

1. Cartographic input data

Table S1. Dataset used as input for spatial analysis

Map	Source*	Data	Scale
States of Brazil	IBGE	2010	1:100,000
Brazilian Biomes	IBGE	2011	1:5,000,000
Urban areas within Brazilian census tracts	IBGE	2010	1:100,000
Hydrographic network	ANA	2010	1:100,000
Remaining native vegetation in Brazil	CSR	2016	1:250,000
Elevation (ASTER Global Digital Elevation Map)	NASA	2015	1:50,000
Absolute Forest Code balance per watershed	CSR	2014	1:250,000
Land use in Brazil in 2012 (OtimizAgro)	CSR	2016	1:250,000
Simulated land use in Brazil in 2030 (OtimizAgro)	CSR	2016	1:250,000
Pastureland prices in Brazil	CSR	2016	1:250,000
Forested land prices in Brazil	CSR	2016	1:250,000
Brazil historical land use (1940-2012) - Planted pasture intensity	Dias *et al* 2016	2016	1:250,000
Historical average precipitation (30-year period / Climatological Normal)	INMET	2015	1: 100,000
Priority areas for flora conservation (Ecological Economic Zoning)	ZEEMG	2006	1:50,000
Priority areas for fauna conservation (Ecological Economic Zoning)	ZEEMG	2006	1:50,000
Index of superficial water availability (Areas under water stress)	ANA	2013	1:100,000
Potential vegetation biomass	Soares Filho *et al* 2016	2016	1:5,000,000

* IBGE – Instituto Brasileiro de Geografia e Estatística / Catalogo de Metadados (http://www.metadados.geo.ibge.gov.br/geonetwork_ibge/srv/por/main.home)
ANA – Agência Nacional de Águas / Portal de Metadados Geoespaciais (http://metadados.ana.gov.br/geonetwork/srv/pt/main.home)
CSR – Centro de Sensoriamento Remoto / Servidor de Mapas (http://maps.csr.ufmg.br/)
INMET – Instituto Nacional de Meteorologia / BDMEP - Banco de Dados Meteorológicos para Ensino e Pesquisa (http://www.inmet.gov.br/portal/index.php?r=bdmep/bdmep)
ZEEMG – Zoneamento Ecológico do Estado de Minas Gerais (http://www.zee.mg.gov.br/)

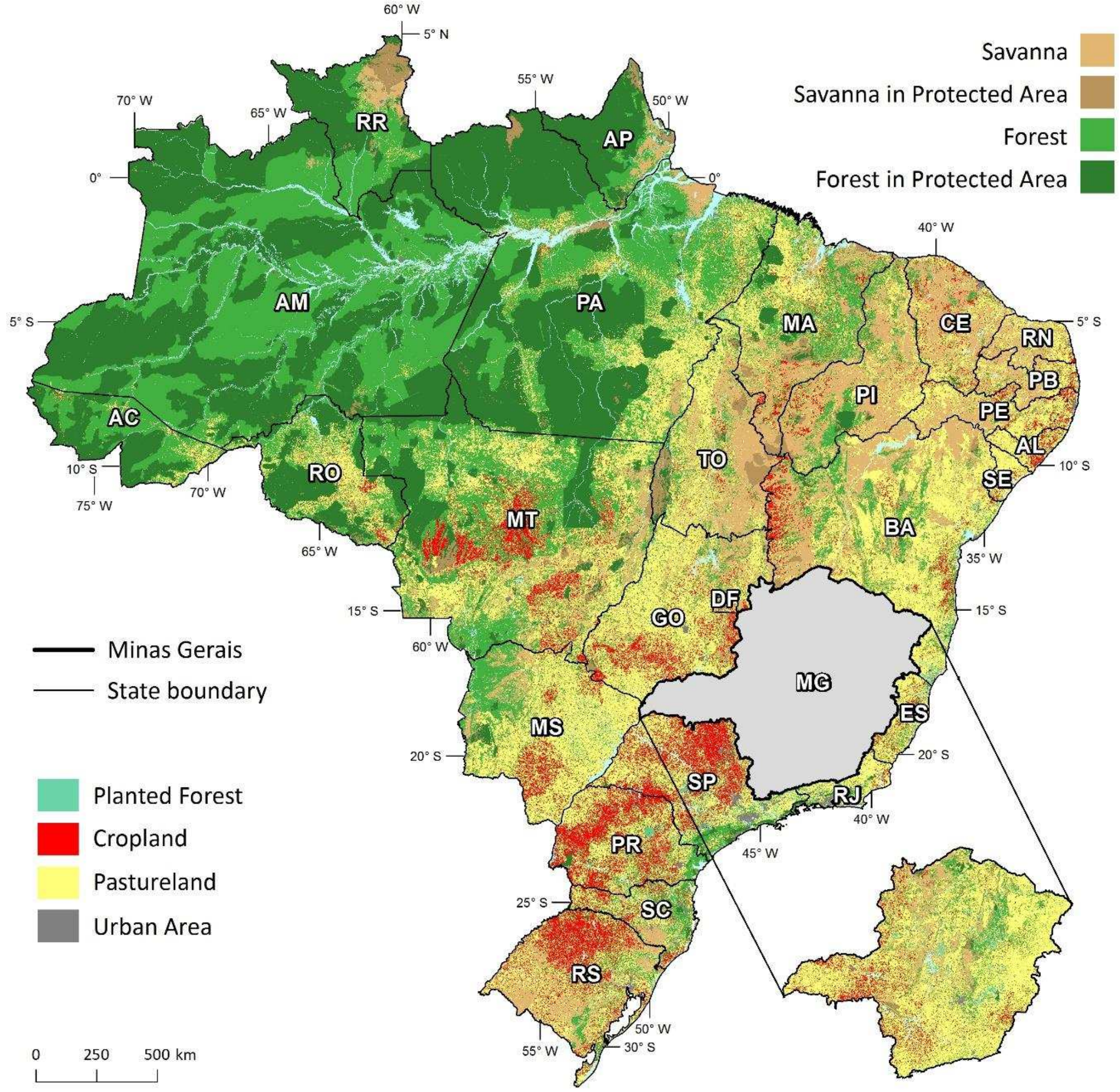

Figure S1: Land use in Brazil and Minas Gerais state in 2012 from Soares-Filho *et al* (2016).

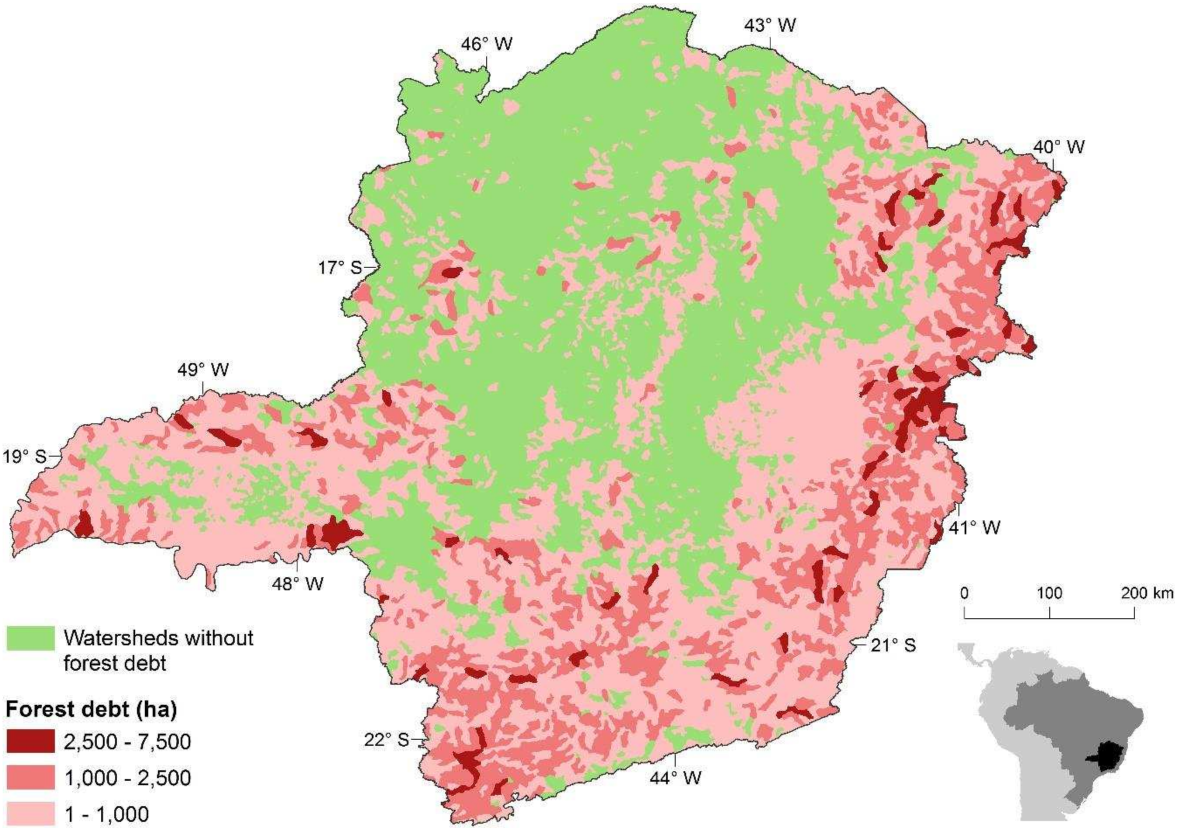

Figure S2: Forest Code debt in Minas Gerais state according Soares-Filho *et al* (2014).

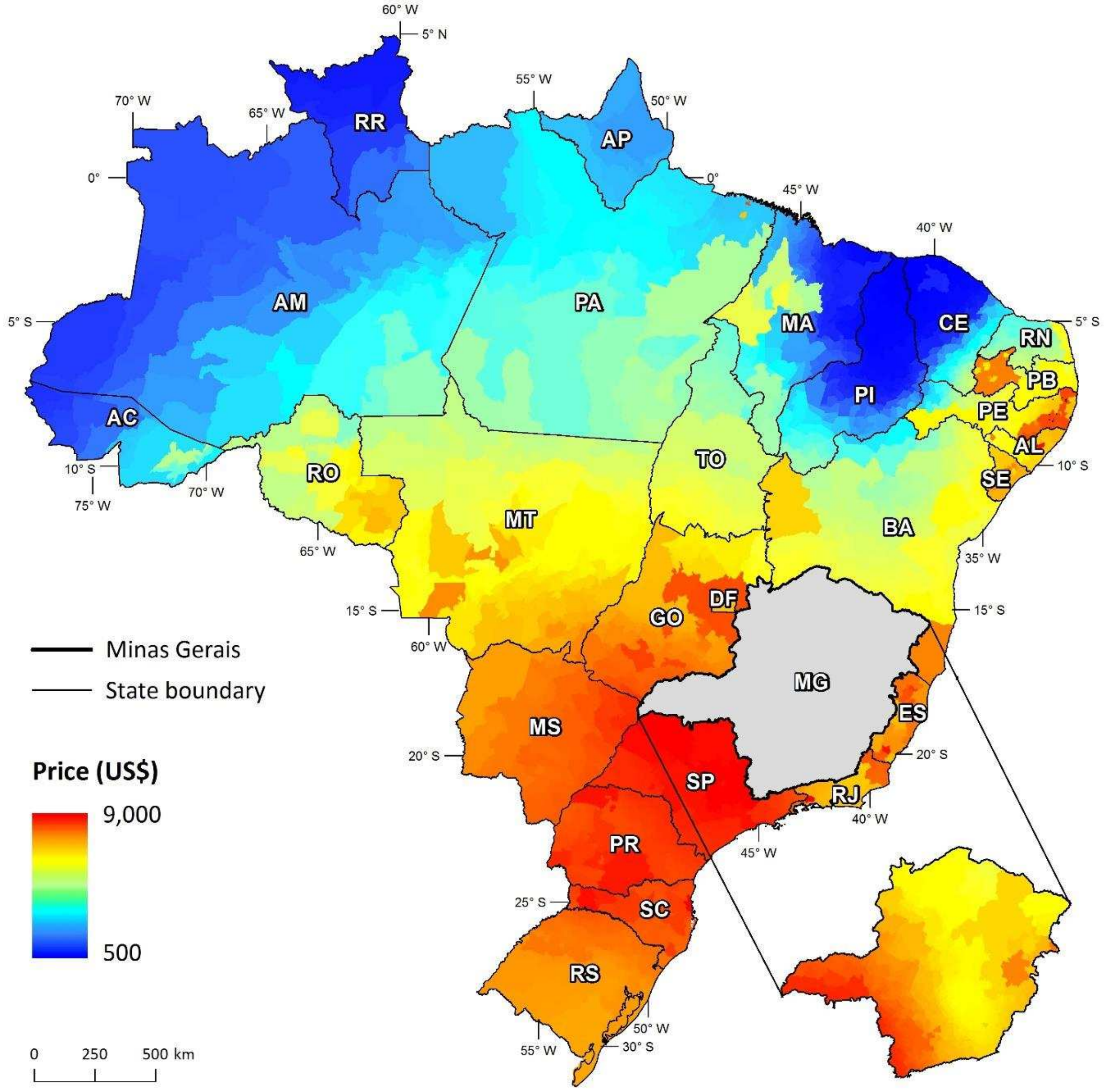

Figure S3: Pastureland prices from Soares-Filho *et al* (2016).

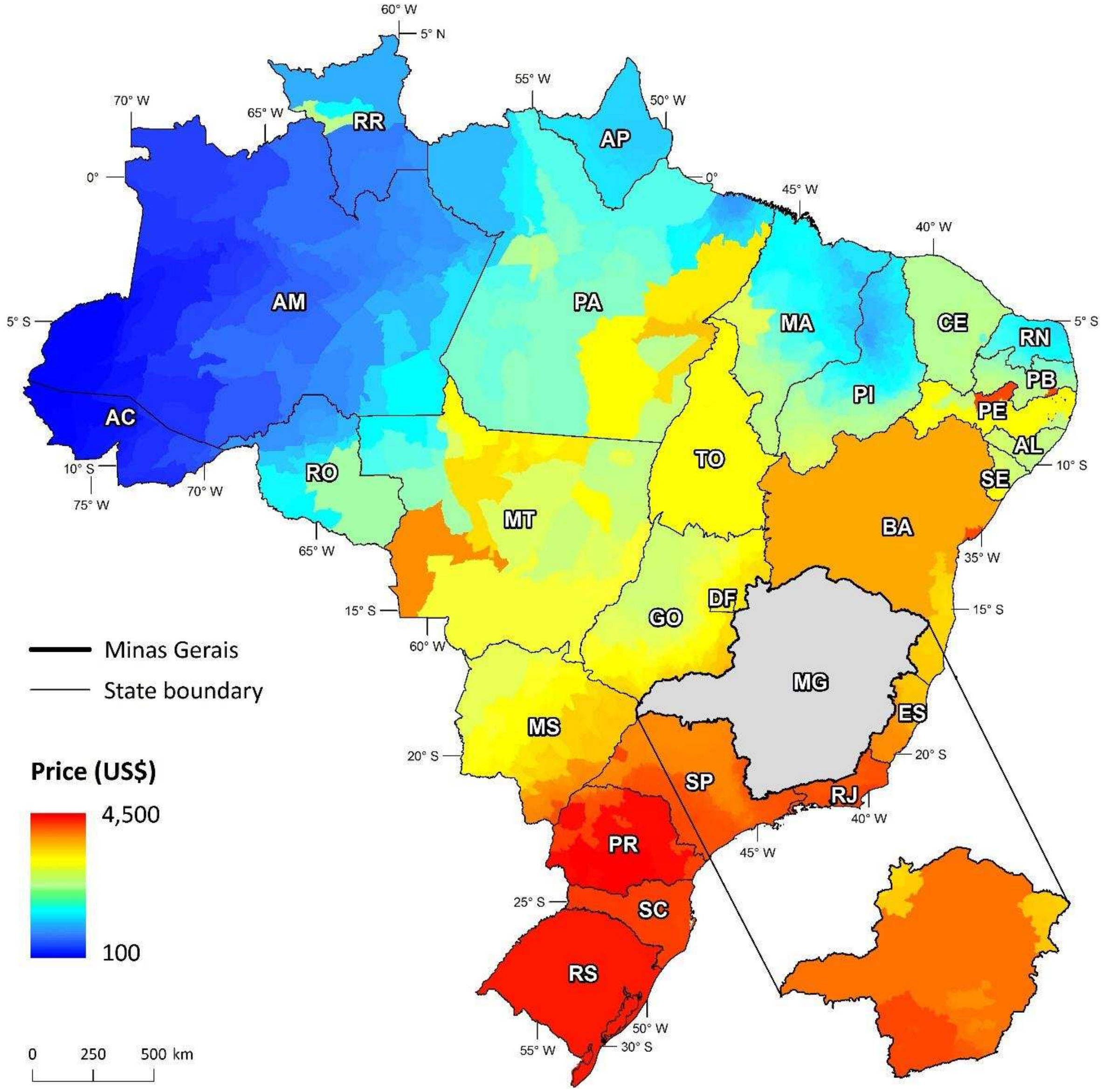

Figure S4: Forested land prices from Soares-Filho *et al* (2016).

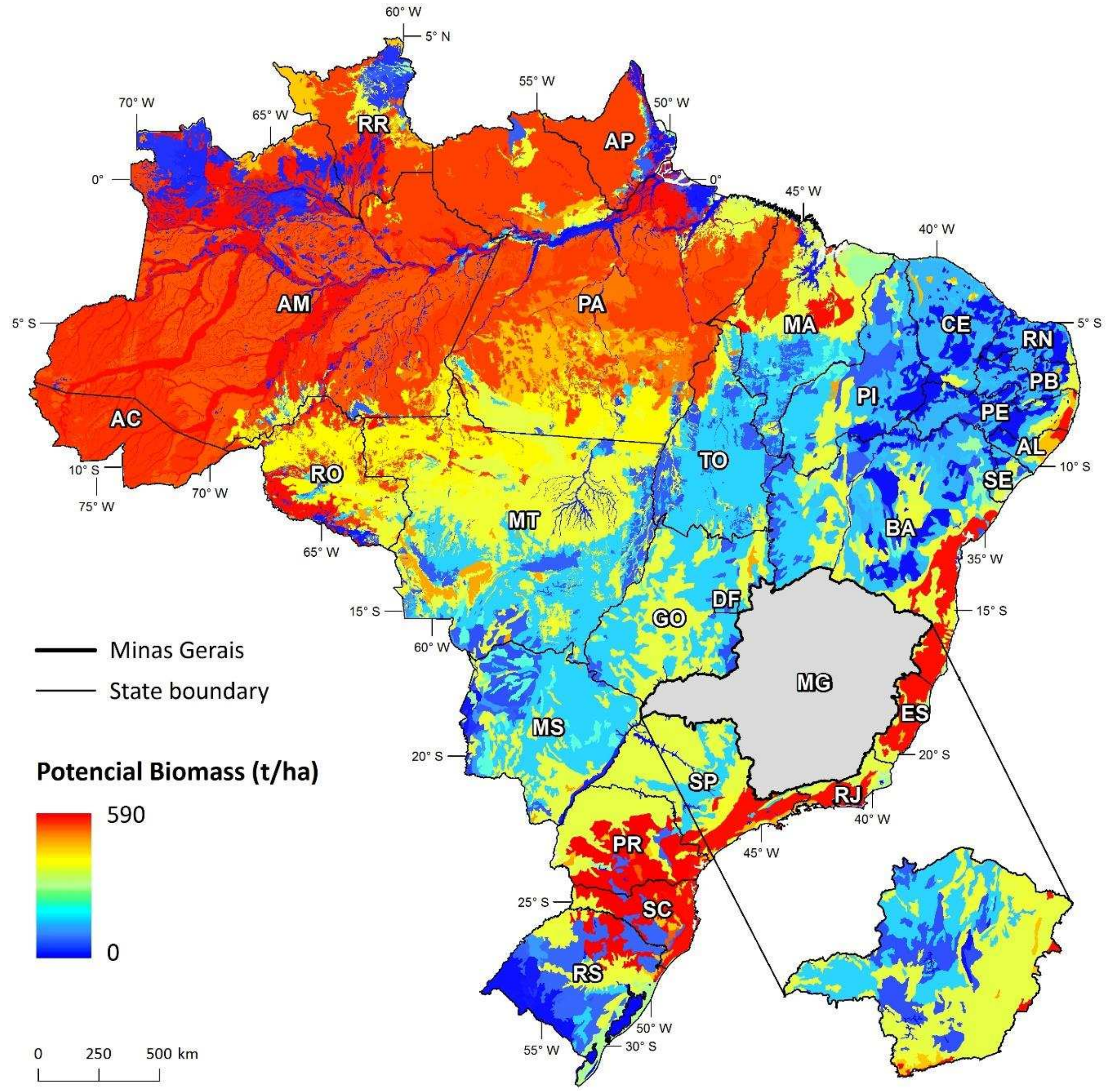

Figure S5: Potential above and below ground biomass from Soares-Filho *et al* (2016). Values greater than 305t/ha were used to select priority restoration areas for enhancing carbon sequestration.

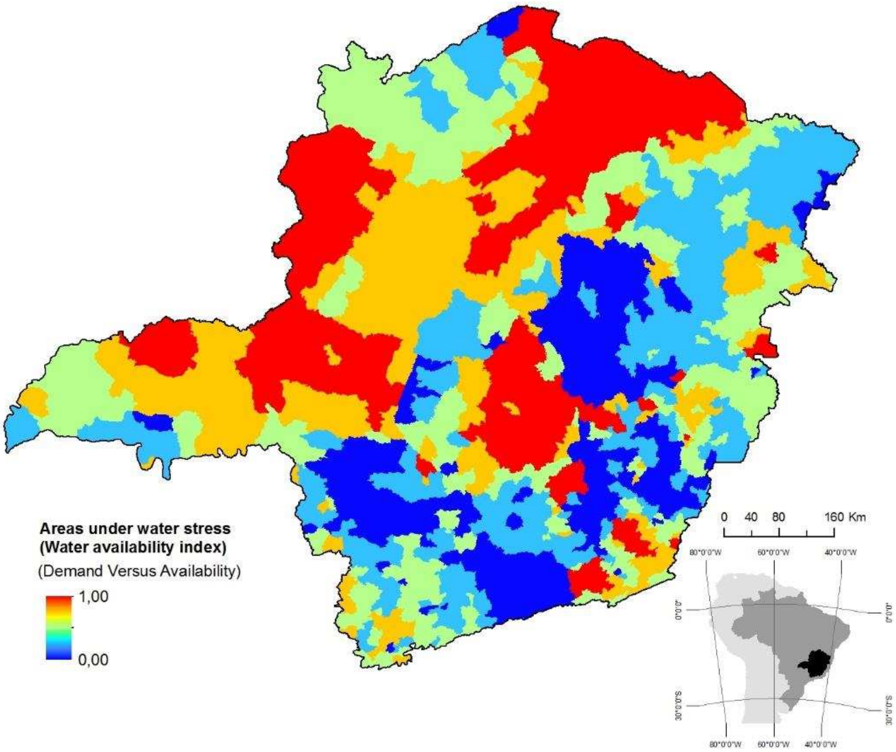

Figure S6. Map of priority areas for water protection (ANA 2013). Values greater than 0.5 were used to select priority restoration areas for enhance water protection.

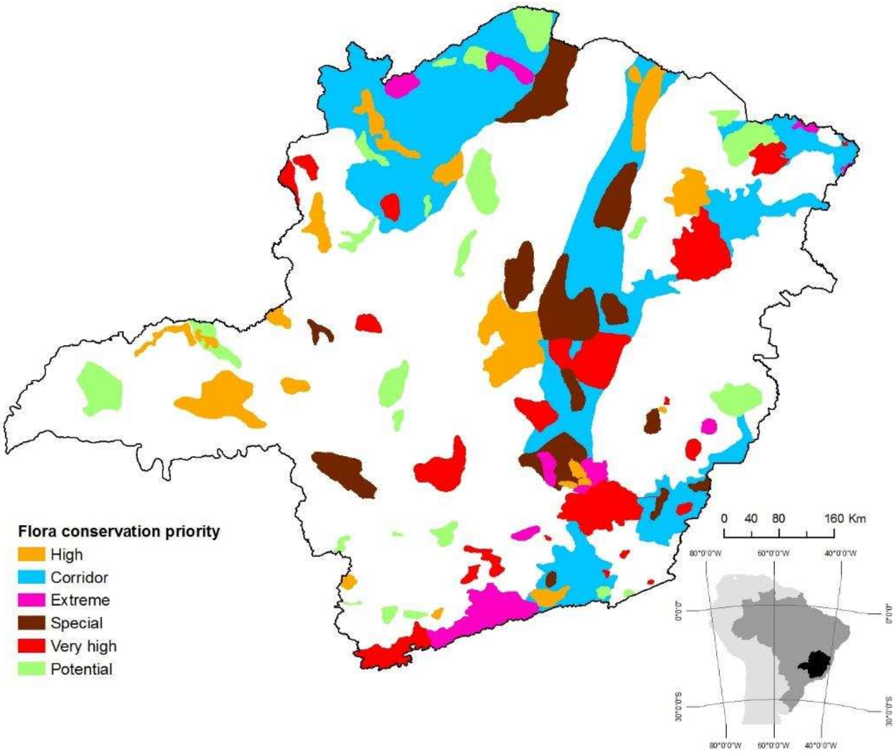

Figure S7. Map of priority areas for flora conservation from Minas Gerais State Ecological-Economic Zoning (ZEEMG 2006).

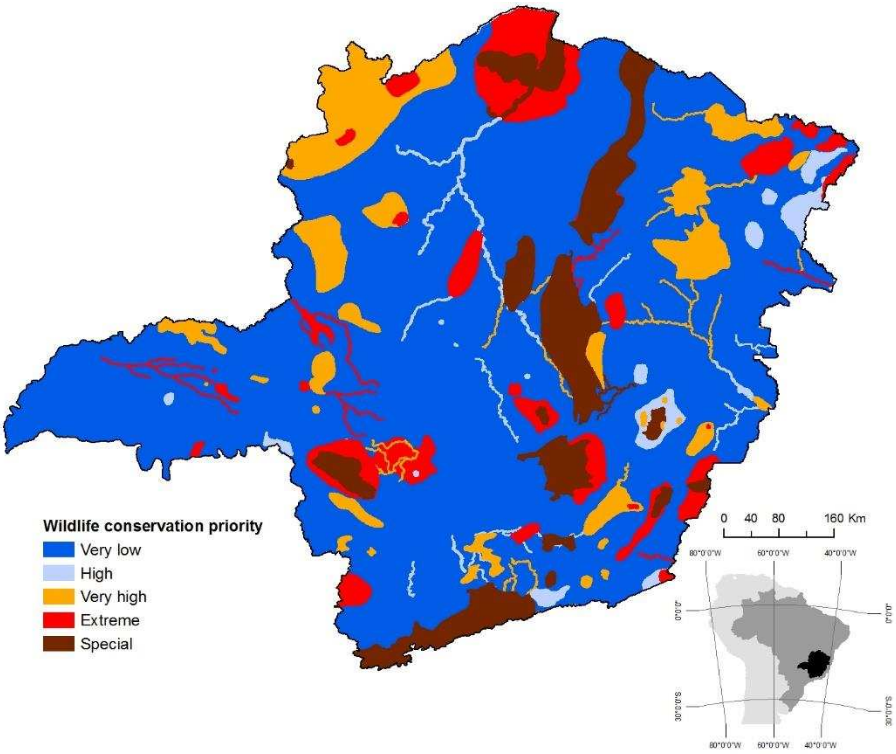

Figure S8. Map of priority areas for fauna conservation from Minas Gerais State Ecological-Economic Zoning (ZEEMG 2006).

2. Spatial analysis and restoration simulations

2.1 Identifying concave areas and low-lying topographic areas

Spatial analysis and restoration simulations were performed using Dinamica EGO freeware (Soares-Filho *et al* 2013). Dinamica EGO consists of a sophisticated platform for environmental modeling for the design from the very simple static spatial model to very complex dynamic ones, which can involve a series of complex spatial algorithms for the analysis and simulation of space-time phenomena.

We used the “Calc Flow Direction Map” functor (http://csr.ufmg.br/dinamica/) to calculate a flow direction map using the elevation map of Minas Gerais state (Aster, 30 meters) (NASA 2015). The values in the output map indicate the directions for each cell as follows:

32	64	128
16	x	1
8	4	2

where X is the current cell and the other cells indicate their corresponding position mask. The resulting directions can be summed to pack several directions in a single value.

That output, in turn, is used to calculate the cumulative flow map using the “Calc Cumulative Flow Map” functor to estimate a cumulative flow map using the flow direction map, the elevation map and a flow partition map. The resulting map indicates the flow received by every cell directly and indirectly. Next, the model scans the entire map searching and selecting the largest central values (after testing if the cell has the higher value locally) within a window of 300m X 300m. Finally, to map these concave areas and low-lying topographic areas (accumulation areas, 300m), we subtracted urban areas and water bodies (Figure S1).

2.2 Histogram equalization

Histogram equalization (Gonzalez and Wood 2008) is calculated by using the following equations for each landscape factor related to natural regeneration potential:

$$\boldsymbol{Eq(1)}: \boldsymbol{px(i) = p(x = i) = \frac{ni}{n}, 0 \leq i < L}$$

Where: px (i) = image's histogram for pixel value i, normalized to [0.1].,
ni = number of occurrences of level i, n = total number of pixels in the image, and L = total number of levels in the image.
Then, a cumulative distribution function corresponding to p_x is defined as follows:

$$\boldsymbol{Eq(2)}: \boldsymbol{cdf_x(i) = \sum_{j=0}^{i} px(j)}$$

Where: cdf$_x$ = the cumulative distribution function or the image's accumulated normalized histogram. Afterwards, a transformation of the form y = T(x) is carried out to produce a new image {y} with a linearized cumulative distribution function (CDF) across the value range, i.e.:

$$\boldsymbol{Eq(3)}: \boldsymbol{cdf_y(i) = iK}$$

where k is a constant. Then, an inverse distribution function is defined as:

$$\boldsymbol{Eq(4)}: \boldsymbol{cdf_y\left(y^{`}\right) = cdf_y\left(T(K)\right) = cdf_x(K)}$$

where k is in the range [0.L]). T maps the levels into the range [0.1], since the model used a normalized histogram of {x}. In order to map the values back into their original range, the following simple transformation needs to be applied on the result as follows:

$$\boldsymbol{Eq(5)}: \boldsymbol{y^{`} = y\,.\,(\max\{x\} - \min\{x\}) + \min\{x\}}$$

Because of the remapping, the lower limit of the resulting histogram can be lower than the minimum value in the input map. The upper limit of the histogram can be greater than the maximum value in the input map or vice-versa. All output maps are reclassified using an equalized approach ranging from 0 to 100 in order to standardize all landscape factors related to natural regeneration potential and allow algebra operations between the maps.

2.3 Allocating pasture to restoration

The restoration simulation uses as a local cellular automata rule (Soares-Filho *et al* 2013) in its transition engine composed of two complementary transition functions, the expander and patcher functors (http://csr.ufmg.br/dinamica/).The former is dedicated only to the expansion or contraction of previous patches of restoration and the latter is designed to generate or form new patches through a seeding mechanism.

To allocate restoration transitions we used the “Patcher and Expander” operation (functor Allocate Transition”) which can be split in two main stochastic processes: choosing a patch seed and forming the patch itself. First, choosing the patch seed is carried out by collecting all cell values (probabilities) were that transition is possible (pastureland), sorting them by their probabilities, and them keeping only the subset of cells with the highest probabilities. The number of cells to keep is calculated multiplying the number of expected transitions by a prune factor parameter (used to specify the size of the vector where cells are ranked for subsequent draw). The resulting cells are the pivot candidate cells or seeds. To choose a seed, one cell is randomly selected using a uniform probability from the pool of pivot candidates and tested to check if it is higher that a second uniform probability. All cells from the subset with the highest probabilities can be selected as long as they go through this process of selection that tends to favor those with higher probabilities (if they are drawn they are more likely to pass the test), but this process not excludes the chance to select those with lower values. After passing the test, the cell is used as a pivot to generate a new patch.

The second process is dedicated to the expansion or contraction of previous patches of a restoration patch by selecting the cell pivot neighbors using a window with 5 lines and 5 columns. The window is centered on the pivot cell and all neighbors where the transitions are possible (pastureland) are collected and placed on a patch formation pool. Then, a cell is drawn from that pool using the same approach used to select a pivot cell, including the rejection test, to be used as part of the patch. If a cell is already in that pool, its probability is increased (or decreased) using the isometry as a factor. Then, the process continues until the number of cells expected for that patch is reached. The number of cells in a patch is chosen as random number from a normal distribution defined using the mean and variance patch sizes.

To calibrate the spatial pattern simulation of the restoration patches, parameters of formation (50% of formation of new patches) and expansion percentage (50% of expansion of existing patches) were calibrated setting the medium size (3 ha), the variance (1.5 ha) and fragment isometry (10). These values aimed to reflect the observed data of regenerated forest fragments under natural regeneration processes by Martins *et al* (2014).

3. Restoration methods dataset

Table S2. Restoration methods, techniques, inputs, services, and costs in Reais (R$)

RESTORATION METHODS AND ACTIVITIES					
Restoration method	**Techniques or practices**	**Inputs**	**Services**	**Total cost per hectare**	**Source**
1) Passive restoration (PASRE)	Fencing	1687.50*	400.00	2087.50	State Environmental System (SISEMA)
2) Assisted natural regeneration (ANR)	Fencing	1687.50*	400.00	2087.50	State Environmental System (SISEMA)
	Fire Protection	0.00	60.00	60.00	
	Control of invasive species	90.00	60.00	150.00	
	Combating ants	60.00	160.00	220.00	
	Management of regenerating individuals	0.00	70.00	70.00	
	Artificial perches	120.00	140.00	260.00	
	Total			3.227.50	
3) Partial planting (PARPLAN)	Fencing	1687.50*	400.00	2087.50	State Environmental System (SISEMA)
	Fencing	1687.50*	400.00	2087.50	
	Fire protection	0.00	60.00	60.00	
	Soil preparation	0.00	426.66	426.66	
	Fertilizing	500.00	200.00	700.00	
	Control of invasive species	90.00	60.00	150.00	
	Seedlings	2097.90**	0.00	2097.90	
	Combating ants	60.00	160.00	220.00	
	Termiticide	50.00	0.00	50.00	
	Planting	0.00	240.00	240.00	
	Replanting	699.30	80.00	779.30	
	Freight		5.29	5.29	
	Total			6816.55	
4) Total Planting (TOTPLAN)	Fencing	1687.50*	400.00	2087.50	State Environmental System (SISEMA)
	Fire protection	0.00	60.00	60.00	
	Soil preparation	0.00	1.280.00	1.280.00	
	Fertilizing	500.00	200.00	700.00	
	Control of invasive species	90.00	60.00	150.00	
	Seedlings	5.247.90**	0.00	5.247.90	
	Combating ants	60.00	160.00	220.00	
	Termiticide	50.00	0.00	50.00	
	Planting	0.00	240.00	240.00	
	Replanting	699.30	80.00	779.30	
	Freight		5.29	5.29	
	Total			10,819.50	
MAINTENANCE 1º YEAR					
	Fire protection	0.00	60.00	60.00	

2) Assisted natural regeneration (ANR)	Combating ants	60.00	70.00	130.00	State Environmental System (SISEMA)
	Control of invasive species	60.00	60.00	120.00	
	Management of regenerating individuals	0.00	140.00	140.00	
	Seed rain translocation	0.00	140.00	140.00	
	Total			530.00	
3) Partial planting (PARPLAN)	Crowing of seedlings	20.00	480.00	500.00	State Environmental System (SISEMA)
	Topdressing	40.00	0.00	40.00	
	Combating ants	0.00	70.00	70.00	
	Fertilizing	150.00	0.00	150.00	
	Fire protection	0.00	60.00	60.00	
	Management of advanced natural regeneration	0.00	70.00	70.00	
	Total			890.00	
4) Total Planting (TOTPLAN)	Crowing of seedlings	20.00	480.00	500.00	State Environmental System (SISEMA)
	Topdressing	40.00	0.00	40.00	
	Combating ants	0.00	70.00	70.00	
	Fertilizing	150.00	0.00	150.00	
	Fire protection	0.00	60.00	60.00	
	Total			920.00	
	MAINTENANCE 2º YEAR				
2) Assisted natural regeneration (ANR)	Fire protection	0.00	60.00	60.00	State Environmental System (SISEMA)
	Combating ants	60.00	70.00	130.00	
	Management of regenerating individuals	0.00	70.00	70.00	
	Seed rain translocation	80.00	70.00	150.00	
	Total			410.00	
3) Partial planting (PARPLAN)	Crowing of seedlings	0.00	400.00	400.00	State Environmental System (SISEMA)
	Combating ants	60.00	70.00	130.00	
	Fire protection	0.00	60.00	60.00	
	Management of advanced natural regeneration	0.00	70.00	70.00	
	Total			660.00	
4) Total Planting (TOTPLAN)	Crowing of seedlings	0.00	400.00	400.00	State Environmental System (SISEMA)
	Combating ants	60.00	70.00	130.00	
	Fire protection	0.00	60.00	60.00	
	Total			600.00	

* depending on the area to be fenced – 200m / 300m / 400m: 1,125.00 / 1,687.50 / 2,250.00, respectively

** depending on amount of seedlings – 666 / 999 / 1667 per ha : 2,097.90 / 3,146.85 / 5,247.90. respectively

***exchange rate: (1 US$ = 3.33; mean rate of 2015)

Table S3. Rural technical assistance provided by the Rural Technical Assistance Agency - EMATER/MG. Activities and costs in Reais (R$)

Rural technical assistance dataset			
Technical assistance costs for restoration projects (LR and PPR)			
Work hours		80.00	Without bank financing
Tansportation, food, and stay costs	Cost per km	1.30	Without bank financing
Tansportation, food, and stay costs	Cost per km	19.00	Without bank financing
Environmental compliance projects of LR and PPR with rural credit	Only the development of the project: 0.5%	Percentage charged	Projects with bank financing
Environmental compliance projects of LR and PPR with rural credit	Elaboration and technical support: 2%	Percentage charged	Projects with bank financing
Samples and Agricultural State Programs covered to estimate the average costs			
Towns served	789 (93% of the state)		
Minas Sem Fome project	250,000 farmers		
Certifica Minas Café project	1633 properties in 214 towns		
Programa Minas Leite project	1160 properties in 386 towns		
PNAE e PAA projects	17 thousand farmers		
Brasil Sem Miseria project	8.2 thousand families until November		
Jaíba Project	1830 producers attended		
Preservação da Bacia do São Francisco project	56 municipalities		
Professionals	400 technicians		
Vehicles	400 units		
Notebooks	640 units		

* Exchange rate: (1 US$ = 3.33; mean rate of 2015)

Table S4. Monitoring, analysis, and evaluation preliminary costs in Reais (R$)

Regional Environmental Regularization Office of Januaria/Minas Gerais

Inputs/Activities	**Costs/efforts**	**Detailed information**	
Land use registry and validation	35 Registrations	35 registrations were completed by 3 employees, with an average estimate of 2 hours spend for each register.	
3 employees	2.91 days for each employee	Each employee works on average 40 hours / month	
Environmental Manager	3 employees	Each employee works on average 40 hours / month	
Environmental Technical	2 employees	Each employee works on average 40 hours / month	
MGS	3 employees	Each employee works on average 40 hours / month	
Northwest Regional Office (sample)			
Maturity	3 employees at a cost of 4,542.40	Each employee works on average 40 hours / month	Number of employees: 3
Daily	1 employee at a cost of 1,563.55	Each employee works on average 40 hours / month	Focal point: 1
Estimated cost for SICAR registry	504.69 per each validation	Validation needed (expected): 570,000 – 590,000 registries / 3 years	
Maintenance and update of information technology systems	764,000 per year	Analysis and validation	
Capacity building and operational costs	386,00 per year	Analysis and validation	
Estimates of land-use registry validation		**308 to 317 million**	

* Exchange rate: (1 US$ = 3.33, mean rate of 2015)

Table S5: Administrative costs of the State Program “Bolsa Verde”. Costs in Reais (R$)

Item	Phase	Type of cost	Total
Preparation Notice	Pre-Announcement	Salary, labor charges	27,000
Celebration Partnerships	Pre-Announcement	Daily work	2,100
Celebration Partnerships	Pre-Announcement	Vehicle	25,000
Celebration Partnerships	Pre-Announcement	Fuel	1,200
Celebration Partnerships	Pre-Announcement	Office supplies, salary, labor charges	18,000
Celebration Partnerships	Pre-Announcement	Service provision (IOF Publishing)	6,384
Capacity	Pre-Announcement	Daily work	8,400
Capacity	Pre-Announcement	Vehicle	25,000
Capacity	Pre-Announcement	Fuel	3,000
Capacity	Pre-Announcement	Material disclosure Program	3,000
Divulgation	Pre-Announcement	Material disclosure Program	1,000
Receiving proposals	Register	Daily work	540,540
Receiving proposals	Register	Vehicle	173,333.33
Receiving proposals	Register	Fuel	46,800
Receiving proposals	Register	Vehicle maintenance	6,500
Receiving proposals	Register	GPS	6,500
Receiving proposals	Register	PC e GIS	32,500
Receiving proposals	Register	Office supplies	3,250
Receiving proposals	Register	Camera	9,100
Receiving proposals	Register	Salary, labor charges	117,000
Receiving proposals	Register	Salary, labor charges	9,000
Analysis of proposals	Analysis	Salary, labor charges	60,000
Analysis of proposals	Analysis	Daily work	50,400
Analysis of proposals	Analysis	Vehicle	130,000
Analysis of proposals	Analysis	Fuel	15,600
Analysis of proposals	Analysis	Office supplies	3,250
Analysis of proposals	Analysis	PC e SIG	50,000
Analysis of proposals	Analysis	Analysis for resources	10,000
Publishing results	Results	Service provision (IOF Publishing)	425.60
Results resources	Post-results	Salary, labor charges	18,000
Results resources	Post-results	Office supplies	0
Results resources	Post-results	Service provision (IOF Publishing)	425.60

Results resources	Post-results	PC e SIG	7,500
Benefit payment (p1)	Payment	Salary, labor charges	27,000
Benefit payment (p1)	Payment	Salary, labor charges	9,000
Benefit payment (p1)	Payment	Salary, labor charges	3,000
Benefit payment (p1)	Payment	Salary, labor charges	117,000
Benefit payment (p1)	Payment	Daily work	98,280
Benefit payment (p1)	Payment	Vehicle	130,000
Benefit payment (p1)	Payment	Fuel	93,600
Benefit payment (p1)	Payment	Office supplies	6,500
Benefit payment (p1)	Payment	Benefit PSA	19,184,166
Verification and monitoring	Monitoring	Salary, labor charges	63,000,00
Verification and monitoring	Monitoring	Salary, labor charges	273,000
Verification and monitoring	Monitoring	Daily work	434,700
Verification and monitoring	Monitoring	Vehicle	130,000
Verification and monitoring	Monitoring	Fuel	109,200
Verification and monitoring	Monitoring	Office supplies	3,250
Verification and monitoring	Monitoring	Vehicle maintenance	13,000
Total cost	**with payments**		**22,104,904.53**
Total cost	**without payments**		**2,920,738.53**

* Exchange rate: (1 US$ = 3,33; mean rate of 2015)

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