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PABLO HENRIQUE DA SILVA

Investigando o impacto das mudanças climáticas sobre a produtividade e o serviço de polinização em *Caryocar brasiliense*

Anápolis, 2018.

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Dissertação apresentada ao Programa de Pós-Graduação Stricto Sensu em Recursos Naturais do Cerrado, na Universidade Estadual de Goiás para a obtenção do título de Mestre em Recursos Naturais do Cerrado.

Orientador: Paulo De Marco Júnior

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Dados do autor (a)

Nome Completo: Pablo Henrique da Silva

E-mail: phecosilva@gmail.com

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Paulo De Marco Junior
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PABLO HENRIQUE DA SILVA

INVESTIGANDO O IMPACTO DAS MUDANÇAS CLIMÁTICAS SOBRE A PRODUTIVIDADE E SERVIÇO DE POLINIZAÇÃO EM *Caryocar brasilisense*

Dissertação defendida no Programa de Pós-Graduação *Stricto Sensu* em Recursos Naturais do Cerrado da Universidade Estadual de Goiás, para a obtenção do grau de Mestre, aprovada em 26 de fevereiro de 2019, pela Banca Examinadora constituída pelos seguintes professores:

Paulo De Marco Júnior

Prof. Dr. Paulo De Marco Júnior
Presidente da banca
Universidade Federal de Goiás

Rafaela Ap. da Silva

Profª. Drª. Rafaela Aparecida da Silva
Membro externo
Universidade Federal de Goiás

Prof. Dr. João Carlos Nabout
Membro interno
Universidade Estadual de Goiás

DEDICATÓRIA

A todas as pessoas que acreditam que o conhecimento pode salvar o mundo.

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Gostaria de agradecer... Sim, eu gostaria, mas acho fundamental que vocês me conheçam antes de sair falando o porquê sou grato. Primeiro vou contar para vocês a parte engraçada da minha trajetória e por qual motivo sou lembrado até hoje pelos meus colegas de turma, e claro, por alguns professores. Sempre tive muitas dificuldades em fazer comunicações orais e lidar com o público, mas *"um belo dia resolvi mudar e fazer tudo o que eu queria fazer"*.

É obvio que não tive uma mudança excepcional, mas tudo tem um começo. E lá vou eu mais uma vez encarar o desafio de me apresentar em público. No Seminário de Apresentação de Projetos decidi que iria fazer uma piada modificada a partir de um vídeo viral, o qual eu adaptei para a minha proposta de projeto. A piada não funcionou com todo mundo (é claro!), mas quem sabia do que eu estava falando sorriu. Nesse momento eu não percebi que nem todas as pessoas estão a par do que já aconteceu na internet e me esqueci de esclarecer que era uma piada. Para essas pessoas eu dei um tiro no pé. No entanto, para não te deixar curioso sobre o tamanho dessa munição, é preciso dizer que a piada foi adaptada do vídeo da atriz "Global", Suzana Vieira, e o seu talento indescritível. Enfim, peguei o meu roteiro de vida e segui em frente. Apesar da minha decisão de continuar com a minha vida, talvez seja possível que no momento em que você esteja lendo esse texto alguém esteja fazendo uma piada sobre o meu talento. Sim, possivelmente foi um erro, mas hoje eu sou grato a todas as piadas do mesmo gênero e assunto que eu tive que ouvir desde então.

Algumas coisas são extremamente necessárias, algumas pessoas também, mas tem aquela pessoa que faz a sua vida ter um significado grandioso. Para mim existe apenas uma pessoa e sem ela eu não conseguiria chegar onde estou. Vocês devem estar se perguntando quem é essa pessoa, e a resposta é o mais simples possível. Minha mãe dedicou uma vida inteira ao trabalho e aos filhos. Se hoje estou aqui é porque tive apoio, e continuo sendo apoiado todos os dias. Obrigado mãe! Sou muito grato aos seus esforços para que eu pudesse atingir os meus objetivos.

Da mesma maneira que o mundo não é binário e que não existe apenas uma alternativa correta para as nossas perguntas, é claro que o quadro de pessoas importantes não acaba por aqui. Durante a minha trajetória acadêmica tive a oportunidade de conhecer diversas pessoas, com pensamentos e maneiras diferentes de enxergar o mundo. Isso realmente teve um diferencial enorme na minha vida. Especificamente, no início do meu

mestrado surgiu uma pessoa fantástica. Ela é realmente excepcional! Acredito que me tornei o maior fã dela. Certo dia, estávamos cursando uma disciplina e decidimos fortalecer a nossa parceria fazendo o trabalho final em dupla. Durante o processo dissemos “no sábado a gente submete”. Por incrível que pareça estamos fazendo esse trabalho até hoje. Acho que merecemos uma camiseta com essa frase. Gracielle Higino, você vai mudar o mundo com a divulgação científica (\o///). Sou muito grato por ter te conhecido e aprendido diversas coisas contigo.

“Só para os loucos, só para os raros”. A letra dessa música define essa pessoa. Mas afinal, por que eu sou tão grato? Aqui eu poderia listar os *“13 reasons why”*, mas não estou disposto a dar esse gostinho para ele. *“Confesso impressionado, nunca vi ‘ninguém’ igual. O ‘laboratório’ era um refúgio, um lugar ‘primordial’”*. Foi no laboratório TheMetaLand que tive o prazer de me aproximar dessa pessoa incrível. Nesse mesmo lugar, desenvolvi diversas habilidades que de uma maneira ou de outra foram estimuladas por ele. Acho que eu estava no lugar certo e com a pessoa certa, mas a jornada acabou. Sinto uma necessidade enorme de agradecer por todos os seus ensinamentos e perspectivas de vida. Hoje eu enxergo o mundo de uma maneira diferente e muito disso eu aprendi com ele. Sou muito grato ao meu orientador, o Dr. Paulo De Marco Júnior, por ser uma inspiração.

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Apesar da ordem dos parágrafos, esse foi um dos últimos que eu escrevi pelo simples fato de não saber o que dizer nele. Estava querendo contar uma história excepcional, mas acho que não há como selecionar apenas uma sobre essa pessoa. Foram tantos momentos juntos que já se tornou cotidiano, mas no final de tudo ela merece um prêmio por me tolerar todo esse tempo. Gostaria de agradecer a Rafaela Gonçalves pela sua amizade e dicas para ganhar descontos em aplicativos. Sou muito grato por todos os desafios que encaramos juntos. Fundamos uma Empresa Júnior e lidamos praticamente sozinhos com ela durante um ano, e a partir daí compartilhamos a nossa paixão pelo empreendedorismo. Até hoje nos aturamos. Muito obrigado por ter caminhado comigo durante todo esse trajeto.

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Acima, eu contei sobre algumas pessoas que fazem parte da minha trajetória, mas agora vou falar das pessoas que entraram na minha vida da maneira mais divertida possível. *“Quem são eles? Quem eles pensam que são?”* Bom! Eles são exatamente quem eu gostaria que vocês conhecessem. Mas enfim, para não reforçar todo esse mistério, gostaria de agradecer a todas as bocas que beijei. Um beijo, uma história. Cada pessoa que eu me aproximei tem uma história fantástica por trás. A diversidade de pensamentos e modos de vida que me fizeram refletir sobre o meu posicionamento diante da sociedade brasileira atual. Hoje eu tenho também tenho uma história e vocês fazem parte dela. Muito obrigado!

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I'm convinced I can swim
I'm pretty sure that I have a fin
I dream about going in a pool
I kick and splash and I look real cool
Okay, I've never seen a pool
But I'd like to visit one with you
Yeah, I'm sure it's a fin
I'm convinced I can swim

Art Smelly

SUMÁRIO

RESUMO

A produção de frutos em cultivos agrícolas é resultado de diversos fatores externos que contribuem para o aumento da produtividade ao longo do tempo. Por exemplo, o serviço ecossistêmico de polinização realiza a troca de gametas entre indivíduos de plantas, aumentando a taxa reprodutiva dessas espécies. No entanto, as mudanças climáticas podem alterar a distribuição de plantas e polinizadores, ocasionando uma incompatibilidade espacial que pode resultar em uma menor taxa de visitação, e consequentemente, produção de frutos. O Pequi (*Caryocar brasiliense*) é uma espécie de planta endêmica e amplamente distribuída no Cerrado brasileiro. É polinizada por dois morcegos nectarívoros (*Anoura geoffroyi* e *Glossophaga soricina*) também com distribuições amplas por toda a região Neotropical. O nosso objetivo é avaliar se as mudanças climáticas podem alterar a distribuição dessas espécies, ocasionando uma incompatibilidade espacial entre plantas e polinizadores. O segundo objetivo é avaliar se os cenários futuros de mudanças climáticas podem comprometer a produtividade de frutos de Pequi. Para avaliarmos o efeito das mudanças climáticas sobre a produtividade e serviço de polinização nessa planta, realizamos a Modelagem de Nicho Ecológico. Nesses modelos usualmente utiliza-se registros de ocorrência de espécies para extrair uma faixa de tolerância ambiental onde as espécies são capazes de sobreviver, e após isso é estima-se áreas adequadas para com base nessa informação. Nós encontramos que as mudanças climáticas não exercem um efeito muito forte na distribuição da planta e de seus polinizadores. Assim, o nosso resultado indica que o serviço de polinização se mantém em cenários futuros de mudanças climáticas. O mesmo acontece quando avaliamos somente a produtividade. Em nossos resultados foi possível observar apenas uma retração de áreas com alta produtividade em cenários de mudanças climáticas. Isso pode indicar que as mudanças climáticas não exercem um efeito muito grande em sua distribuição, e consequentemente, sua produtividade. Portanto, o Pequi pode ser um cultivo rentável de acordo com as projeções climáticas que utilizamos.

Palavras-chave: serviço de polinização, produtividade, economia, Modelagem de Nicho Ecológico.

ABSTRACT

The production of fruits in agricultural crops is the result of several external factors that contribute to increase productivity over time. For instance, the pollination ecosystem service performs the exchange of gametes among plant individuals, increasing the reproductive rate of these species. However, climate change can alter the distribution of plants and pollinators, leading to a spatial incompatibility that can result in a lower rate of visitation and, consequently, fruit production. “Pequi” (*Caryocar brasiliense*) is a plant species endemic and widely distributed in the Brazilian Cerrado. It is pollinated by two nectarivorous bats (*Anoura geoffroyi* and *Glossophaga soricina*) also with broad distributions throughout the Neotropical region. Our aim is to evaluate if climatic changes can alter the distribution of these species, causing a spatial incompatibility between plants and pollinators. The second objective is to evaluate if future scenarios of climate change can compromise the productivity of “Pequi” fruits. In order to evaluate the effect of climatic changes on productivity and pollination service in this plant, we performed the Ecological Niche Modeling. In these models, species occurrence records are usually used to extract a range of environmental tolerance where species are able to survive, and after that, it is estimated that adequate areas are based on this information. We found that climate change does not have a very strong effect on the distribution of the plant and its pollinators. Thus, our result indicates that pollination service remains in future scenarios of climate change. The same is true when we evaluating only productivity. In our results, it was possible to observe only a retraction of areas with high productivity in scenarios of climate change. This may indicate that climate change does not have a very large effect on its distribution, and consequently its productivity. Therefore, “Pequi” can be a profitable crop according to the climate projections we use.

Keywords: pollination service, productivity, economy, Ecological Niche Modeling.

APRESENTAÇÃO GERAL

A presente dissertação intitulada "**Investigando o impacto das mudanças climáticas sobre a produtividade e o serviço de polinização em *Caryocar brasiliense***" está dividida em dois capítulos. No primeiro capítulo investigamos o efeito das mudanças climáticas no serviço ecossistêmico de polinização, no qual testamos a hipótese de que as mudanças no clima provocarão uma incompatibilidade espacial entre a distribuição da planta e seus respectivos polinizadores. No segundo capítulo é feita uma abordagem econômica sobre a produção de frutos. Para isso, investigamos a capacidade dos modelos de nicho ecológico em predizer a produtividade. Com isso, também estimamos o efeito das mudanças climáticas na produtividade econômica em *Caryocar brasiliense*. Em ambos os capítulos incorporamos o uso de dados de solo ao modelarmos a planta, assumindo a premissa de que a adição de variáveis de solo pode aumentar a precisão dos Modelos de Nicho Ecológico. Os capítulos seguem as normas de formatação das revistas *Biological Conservation* e *Ecological Economics* respectivamente.

INTRODUÇÃO GERAL

A conservação da biodiversidade tornou-se um tema frequente na comunidade científica (Correa Ayram et al., 2016; Willis and Birks, 2006). Diversos estudos tentam indicar soluções para a conservação, a fim de maximizar a persistência das espécies na natureza (Oliveira et al., 2017; Terrado et al., 2015; Whitehead et al., 2017). No entanto, diversos fatores podem resultar em consequências para a manutenção dessas espécies, tal como a degradação de habitat (Wilson et al., 2016), sobre-exploração (Gallo and Pejchar, 2016), introdução de espécies exóticas (Miller et al., 2016) e mudanças climáticas (Bellard et al., 2012). Identificar esses problemas é uma etapa fundamental para o estabelecimento de ações práticas de conservação. As mudanças climáticas, por exemplo, podem alterar o tamanho da distribuição das espécies, restringindo populações em pequemos fragmentos de áreas adequadas (Martínez-Meyer et al., 2004). Além disso, é possível detectar outros elementos importantes para a conservação de uma espécie. A diminuição na taxa de interações dentro de uma comunidade pode reduzir a sobrevivência de indivíduos (Giannini et al., 2012). Em plantas, o serviço de polinização pode ser considerado um elemento chave para a persistência de espécies, pois a sua ausência pode reduzir a taxa reprodutiva de indivíduos (Zhang et al., 2007). Em espécies de interesse econômico, a associação entre mudanças climáticas e a redução na taxa de polinização pode reduzir o tamanho e a qualidade dos frutos, o que potencialmente pode ocasionar um impacto econômico negativo para a sociedade.

A polinização é um processo ecossistêmico em que indivíduos de outras espécies realizam a troca de gametas entre plantas (Costanza et al., 1997). Em alguns casos, torna-se um serviço ecossistêmico ocasionado pelo benefício desse processo para os seres humanos (Costanza et al., 1997). Para alguns cultivos esse serviço é fundamental para manter a produtividade ao longo do tempo. Apesar disso, essa interação biológica pode ser vulnerável a diversos impactos, o que consequentemente pode afetar a produtividade em plantas (Stout, 2014). As mudanças climáticas, por exemplo, tem sido um dos fenômenos mais discutidos nos últimos anos, e o seu impacto na agricultura tem recebido bastante destaque (Nabout et al., 2011; Settele et al., 2016). A velocidade em que o clima está mudando pode dificultar com que as espécies consigam acompanhar áreas adequadas para sua sobrevivência (Jackson and Overpeck, 2000). Consequentemente, se espécies de plantas não conseguem acompanhar as mudanças climáticas, é bastante provável que as áreas adequadas diminuam e possivelmente reduz suas respectivas taxas reprodutivas. Além disso, a taxa reprodutiva de uma planta também pode ser afetada pelos polinizadores. Por esse motivo, as mudanças climáticas também podem afetar a produtividade de plantas por meio de uma perda da sobreposição das áreas adequadas entre plantas e polinizadores (Schweiger et al., 2008).

Em plantas economicamente importantes, a redução da taxa reprodutiva também pode representar uma perda significativa para municípios que utilizam o extrativismo vegetal como fonte de renda (Gribel and Hay, 1993; Nabout et al., 2011). Entender os fatores que afetam a produtividade dessas plantas pode direcionar esforços para esse tipo de produção. Alguns estudos têm investigado como que as condições ambientais podem afetar a produtividade (Nabout et al., 2011). Em alguns casos utilizam-se características biológicas para entender quais fatores influenciam mais na produção de comida. Conhecer a produtividade potencial de alguns cultivos pode dar suporte na tomada de decisões sobre quais espécies cultivar (Zardo and Henriques, 2011). Isso pode gerar um benefício direto para produtores rurais, pois se a escolha for feita por meio de critérios bem estabelecidos é bastante provável que as consequências econômicas da produção agrícola não afetem municípios que necessitam desse tipo de produção para manter sua renda mensal. Além disso, entender como a produtividade potencial está distribuída no espaço pode dar suporte sobre onde cultivar. No entanto, para mapear essas áreas é necessário o uso de algumas ferramentas que auxiliem na delimitação dessas áreas. Um exemplo frequentemente utilizado na literatura é a Modelagem de Nicho Ecológico (em inglês, Ecological Niche Modeling - ENM).

Modelagem de Nicho Ecológico é um procedimento estatístico que associa registros de ocorrência a suas respectivas condições ambientais observadas (Peterson, 2006). A partir disso, estima áreas adequadas por meio da similaridade ambiental entre locais, comparando as condições ambientais de cada unidade de área à faixa de tolerância ambiental conhecida para a espécie alvo (Soberón and Nakamura, 2009). Esses modelos têm sido utilizados em diferentes abordagens de estudos ecológicos (Papeş and Gaubert, 2007; Velazco et al., 2017). Na literatura é possível listar algumas áreas de conhecimento importantes que utilizam essa ferramenta como suporte para tomadas de decisão (Marini et al., 2010). Como um exemplo, o estabelecimento de áreas prioritárias tem utilizado essa abordagem para selecionar áreas que potencialmente apresentarão condições ambientais favoráveis para a persistência de espécies (Pierce et al., 2005). Além disso, também é possível utilizar mapas de adequabilidade ambiental resultantes dos modelos de nicho para propor outras formas de pesquisa, como as áreas de alta produtividade agrícola e silvicultura.

Ao modelar plantas, a maioria dos estudos utilizam somente dados climáticos para predizer a adequabilidade ambiental (Diniz-Filho et al., 2009; Marco-Júnior and Siqueira, 2009). No entanto, alguns estudos têm incorporados dados de solo na distribuição de plantas (Velazco et al., 2017). Então, assumindo que dados de solo não muda rapidamente com o tempo, é possível que ao integrar esses dados em modelos de distribuição, potencialmente algumas espécies não mudariam muito a suas distribuições, ficando restringidas no espaço geográfico. Então, ao considerar que o serviço de polinização também seja um fator importante na produtividade de plantas, é possível que a adição de variáveis de solo restrinja a distribuição da planta, o que poderia evidenciar uma incompatibilidade espacial entre as plantas e polinizadores (Morton and Rafferty, 2017; Polce et al., 2014; Schweiger et al., 2008). Além disso, pode-se esperar que o uso de dados de solo pudesse complementar o nicho conhecido da espécie a fim de estimar melhores predições para plantas.

A árvore Pequi (*Caryocar brasiliense* Camb. Caryocaraceae) é uma espécie endêmica e amplamente distribuída no bioma Cerrado. Essa é uma das espécies em que o extrativismo vegetal é bastante forte, principalmente por municípios que extraem o fruto dessa espécie para comercializar em mercados locais (Guedes et al., 2017; Nabout et al., 2011). Além disso, é uma espécie comum na culinária da região central do Brasil. O seu fruto é bastante comercializado devido aos seus diversos usos, desde extração de óleos e amêndoas até a alimentação da polpa do fruto (Araujo, 1995). Apesar da diversidade de possibilidades de uso desse fruto, para manter uma alta produtividade é necessário que a espécie seja polinizada, pois a taxa de autopolinização é baixa, necessitando de outras espécies para manter a produção de frutos. Seus polinizadores são duas espécies de morcegos nectarívoros (*Glossophaga soricina* e *Anoura geoffroyi*) (Gribel and Hay, 1993). Além disso, sua importância econômica atraiu o interesse de diversos pesquisadores na área de ecologia. Por esse motivo, existem vários estudos estimando parâmetros populacionais e distribuição potencial. Em particular, estudos investigando a distribuição potencial dessa espécie utilizam somente variáveis climáticas como preditores ambientais.

Nosso objetivo está dividido em dois capítulos em formato de artigos científicos. No primeiro capítulo estamos interessados em estudar o efeito das mudanças climáticas na sobreposição de áreas adequadas entre plana e polinizadores. Para isso, testaremos a hipótese de que em cenários de mudanças climáticas haverá uma perda de sobreposição entre áreas altamente adequadas. Além disso, testamos o pressuposto de que dados de solo podem restringir a distribuição da planta, fazendo com que a sua distribuição no espaço varie menos. No segundo capítulo estamos interessados em investigar a capacidade dos modelos de nicho ecológico em predizer áreas com alta produtividade para o Pequi. Em ambos os capítulos conduzimos os procedimentos de modelagem utilizando dois conjuntos de dados ambientais. Um deles é somente climático e no outro incorporamos os dados de solo.

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The climate change impact on the mismatch between plant and pollinators distributions in the Brazilian Cerrado

Pablo Henrique da Silva[a,b,]* - Paulo De Marco Júnior[b]

[a] Programa de Pós-Graduação em Recursos Naturais do Cerrado – RENAC, Universidade Estadual de Goiás (UEG). BR 153, Quadra Área, Km 99, Bloco IV, 1ª Andar, 75132-903, Anápolis, Goiás, Brazil.

[b] Theoretical Metacommunity and Landscape Ecology Laboratory, Departamento de Ecologia, Instituto de Ciências Biológicas (ICB), Universidade Federal de Goiás (UFG). Rodovia Goiânia-Nerópolis km 5, Campus II Itatiaia, 74001-970, Goiânia, Goiás, Brazil.

* Corresponding author at: Theory, Metacommunity and Landscape Ecology Lab. Instituto de Ciências Biológicas V, Universidade Federal de Goiás, Goiás, Brasil. 74001-970.

E-mail address: phecosilva@gmail.com (P. H. Silva).

1. Introduction

Pollination is an interspecific interaction with strong ecosystem effects on the stability of natural and human-dominated systems (Hadley and Betts, 2012). The lack of pollinators can constrain the development of key plant populations in the ecosystem (Potts et al., 2010) affecting, for example, the succession process (Devoto et al., 2012; Forup et al., 2008). On the other hand, the pollination service affects the productivity of agroecosystems (Kennedy et al., 2013; Marco and Coelho, 2004; Potts et al., 2007), with well-documented large economic effects (Gallai et al., 2009). Therefore, it has the potential to encourage the public interest in biodiversity conservation considering the economic advantages for society (Morandin and Winston, 2006), helping to build public policies for conservation (Chan et al., 2006). This approach was developed mainly in the discussions involving economically important crops (Cristina Giannini et al., 2013; Marco and Coelho, 2004). However, pollination is a vulnerable interaction, since the biological elements involved are sensitive to different impacts (Montero-Castaño and Vilà, 2012; Settele et al., 2016; Stout, 2014). Climate change, for example, can alter the distribution of climatically suitable areas for the survival of both the plant species and its pollinators (Giannini et al., 2012; Pyke et al., 2016), and for the occurrence of pollination, which in turn can have consequences in fruit productivity (Elias et al., 2017; Polce et al., 2014).

The speed at which climate change occurs reduces the chance of species migrating under suitable conditions for their survival (Jackson and Overpeck, 2000). This can reduce the species distributional size, which may cause temporal and spatial mismatch between plants and pollinators, whereas, as a consequence, affects the fitness and population dynamics in plants (Hegland et al., 2009; Schweiger et al., 2008). Furthermore, the soil, as a static component, restricts plants' dispersion (Schweiger et al., 2008; Velazco et al., 2017), but do not affect directly the distribution of pollinators. A consequence of this would be the loss of plant and pollinators overlapping distribution under effect of climate change, decreasing the probability of pollination (Silva et al., 2014). The study of how climate change affects interactions, however, involves several methodological issues that have only recently begun to be circumvented (Morton and Rafferty, 2017).

The most common technique for the study the geographical distribution of species is the Ecological Niche Modeling (ENM). These models are simplifications of the patterns of species' distribution in the nature based on their environmental requirements (Peterson and Soberón, 2012). Their algorithms use observed environmental data at the occurrence records to predict suitable areas by means of environmental similarity between sites, considering the assumption that the species' niche does not change. Usually, climate has been used as macroscale environmental data to these analyses (Ackerly et al., 2010; Pearson and Dawson, 2003). This allows the study of species distribution in different scenarios, both in space and time. The ENMs are statistical procedures based mainly in theory of ecological niche, in which individuals of the same species are associated with a set of environmental conditions and resources that define and limit their distribution (Soberón, 2007).

The "Pequi" tree (*Caryocar brasiliense* Camb, Caryocaraceae) is an endemic species broadly distributed in the Cerrado ecoregion. The fruit of this species is used for direct consumption and for the extraction of other materials (Araujo, 1995), which makes it very important for regional economy. The reproductive system in this plant consists of hermaphrodite and auto compatible flowers, but the fitness in *C. brasiliense* depends in large part on the cross-pollination (Gribel and Hay, 1993). This helps to reduce the number of aborted seeds, which is strongly associated with high rates of self-pollination (Collevatti et al., 2009). The pollination service in this species is provided by two species of nectarivorous bats: *Glossophaga soricina* and *Anoura geoffroyi* (Gribel and Hay, 1993). These pollinators present broad geographical distribution and are considered not threatened (LC - low concerns) according to the IUCN criteria (IUCN, 2018). Nevertheless, some studies already predicted a change in the geographical distribution of *C. brasiliense* in climate change scenarios (Collevatti et al., 2011a; Nabout et al., 2011).

Our goal is to evaluate the climate change consequences on geographic range of plant-pollinator interactions. Here, we assume that soil data constraint plants distribution in climate change scenarios. We hypothesize that there will be a loss of overlap between present and future spatial distribution of plants and its pollinators in climate change scenarios. Otherwise, this analysis may provide a more realistic evaluation of climate change effects on a food resource ("Pequi") with high importance in a portion of Brazilian national market.

2. Methods

2.1. Species Distribution Database and Data Treatment

To describe completely the environmental niche of these species (Raes, 2012), we used all the occurrence records from a systematic review of the literature available on Web of Science and Scopus, with the search codes: ("*Caryocar brasiliense*" OR "*C. brasiliense*" OR "*Caryocar brasiliense* Cambess" OR "pequi" OR "piqui" OR "pequizeiro" OR "piquizeiro");

("*Glossophaga soricina*" OR "*G. soricina*" OR "bat list"); (“*Anoura geoffroyi*” OR “*A. geoffroyi*” OR “bat list”). Moreover, we completed the occurrence records using two online databases: (1) GBIF (https://www.gbif.org/); and (2) SpeciesLink (http://splink.cria.org.br/). All data collected, especially those from online database, were evaluated considering various quality criteria (De Giovanni et al., 2012). We considered possible georeferencing errors (duplicated occurrence records, latitude and longitude exchange, and occurrence records outside the Neotropical region), and taxonomic identification accuracy (mainly for species of the “Pequi” tree). We removed all occurrences considered to be doubtful in relation to these criteria, which improved the quality and reliability of the data to be used in the models.

2.2. Environmental variables

We separated the environmental data in two sets to perform the ENMs: (1) climate-only; (2) climate and edaphic variables together. Climate data were obtained from WorldClim database (http://www.worldclim.org/), and the current climate scenario was based on interpolations of meteorological data collected in the period from 1960 to 1990. For the future scenario, we used 17 climate models for the year of 2070 from the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). These data are climate projections calibrated using as baseline current climate, and we used only one (Representative Concentration Pathways 8.5) for the following climate models: ACCESS1-0, BCC-CSM1-1, CCSM4, CESM1-CAM5-1-FV2, CNRM-CM5, GFDL-CM3, GFDL-ESM2G, GISS-E2-R, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, INMCM4, IPSL-CM5A-LR, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MPI-ESM-LR, MRI-CGCM3, NorESM1-M. Edaphic data were obtained from the SoilGrids database available from International Soil Reference and Information Centre (ISRIC, https://www.isric.online/), which describe physical and chemical properties of the soil (Hengl et al., 2014). From this dataset, we selected eight variables that we considered important for Cerrado plants: (1) Depth to bedrock (R horizon) up to 200 cm; (2) Probability of occurrence of R horizon; (3) Cation exchange capacity of soil in cm olc/kg; (4) Clay content (0-2 micrometer) mass fraction in %; (5) Soil pH x 10 in H_2O; (6) Soil pH x 10 in KCl; (7) Silt content (2-50 micro meter) mass fraction in %; and (8) Sand content (50-2000 micro meter) mass fraction in %.

Both for the choice of climate and edaphic variables, and the general procedures of modeling we followed Velazco et al. (2017), who made a very complete account of the use of those variables for model plant distributions in South America. Original climate and edaphic data has a spatial resolution of 30 arc-seconds (≈1 km² cell size). We upscaled them to 5 arc-minutes (≈10 km cell size) for all analysis using the average value of the higher resolution cells into lower resolution cells. In addition, in order to reduce multicollinearity among the environmental variables, we used a Principal Component Analysis (PCA) in the two datasets (climate-only, climate and edaphic variables together) (De Marco and Nóbrega, 2018). PCA is a multivariate technique that reduces the dimensionality of a large dataset, initially correlated. A recent work has evaluated the use of PCA transformed variables into ENM and found an increase of accuracy for different algorithms. This also reduces the complexity of the algorithms of ENMs, which avoids the production of unrealistic predictions. We selected the axes that represent 95% or more of the total variation of the original environmental matrix.

2.3. Modeling procedures and evaluation of models

The ENMs are statistical procedures that relate the environmental variables with the occurrence points to predict suitable areas for the species. Here, we used five algorithms of ENMs with the purpose of measuring the uncertainty associated with these procedures, producing better consensus maps among them: (1) Maximum Entropy (MXS) reduce complexity and predict better models in specific situations (Phillips et al., 2017, 2004); (2) Random Forest (RDF) adjust the distribution models based on decision trees (Prasad et al., 2006); (3) Support Vector Machine (SVM) creates a separation line between the occurrence records and a set of absences (Guo et al., 2005); (4) Maximum Likelihood (MLK) estimates a probability distribution of occurrence based on the environmental conditions of the presence records (Royle et al., 2012); e (5) Gaussian (GAU) predicts the probability of occurrence based on adjustments made by Bayesian inference (Golding and Purse, 2016). Typically, these ENMs need real absences to be adjusted, with exception of the MXS, which adjust the models by the difference between the occurrence records and a sample of all background. Nevertheless, real absences are rare; as an alternative we used pseudo-absence to adjust these algorithms. For this purpose, we created a bioclimatic envelope as a pseudo-absence selection method and only unsuitable areas for the species are considered. This method is advised because it reduces the possibility of a real presence not recorded in our database to be included as a pseudo-absence in the analysis (Muscarella et al., 2014).

The ENMs evaluations were performed using geographic partition in a checkerboard format. This partition method subdivides the study extent equally and selects, alternately, training (to perform the model) and testing (to evaluate the models) occurrences (Muscarella et al., 2014). The algorithms performances were estimated by the True Skill Statistics (TSS), using True Positive Rate (TPR) and True Negative Rate (TNR) metrics. This procedure has already been compared with other metrics and; therefore, considered as a simple and intuitive measure to evaluate the performance of the ENMs (Allouche et al., 2006).

In order to test the general hypothesis of this work, we produced consensus maps with only the grid cells that the models agreed to. However, there are many different techniques to produce consensus maps (Marmion et al., 2009). For the purpose of this study, we used the sum of models that present TSS values above average. In addition, we made presence and absence maps using a threshold at which the sum of the sensitivity and specificity is highest (Liu et al., 2011). We applied this consensus procedure initially to the models from different algorithms at the present environment. In the projection of the future climates the problem is more complex once we have the variation among the algorithms and among different climate scenarios. To allow an evaluation of the uncertainty derived from the climate scenarios, we performed the above method for all algorithms within each climate scenario separately. Thus we have 19 different final future distributions for each species and could evaluate our hypothesis for each of these results. All modeling procedures was done using ENM_TheMetaLand package in software R (https://github.com/andrefaa/ENM_TheMetaLand).

2.4. Experimental Design and Analytical Procedures

The experimental design of this study consists on the comparison between the potential pollination service estimated by the ENMs, considering the current and future climate scenarios. We assume that highly suitable areas for the bat species are a surrogate of its presence (and possibly abundance) (VanDerWal et al., 2009) and, thus, may be converted into a quantitative estimate of the availability of the pollination service. Our basic assumption is that the plant species will be constrained by both climate and edaphic variables, while the bats are only affected by climate. Thus, we expect that the plant will experience less distributional change than its pollinators, favoring a disconnection of its distributions. To evaluate these possibilities and the possible effect of edaphic variables as a constraint to plant distribution in future climates, we used both (1) climate and (2) climate + edaphic variables in plant models (Fig. 1). Otherwise, we modeled bat pollinator distributions based only on climate variables.

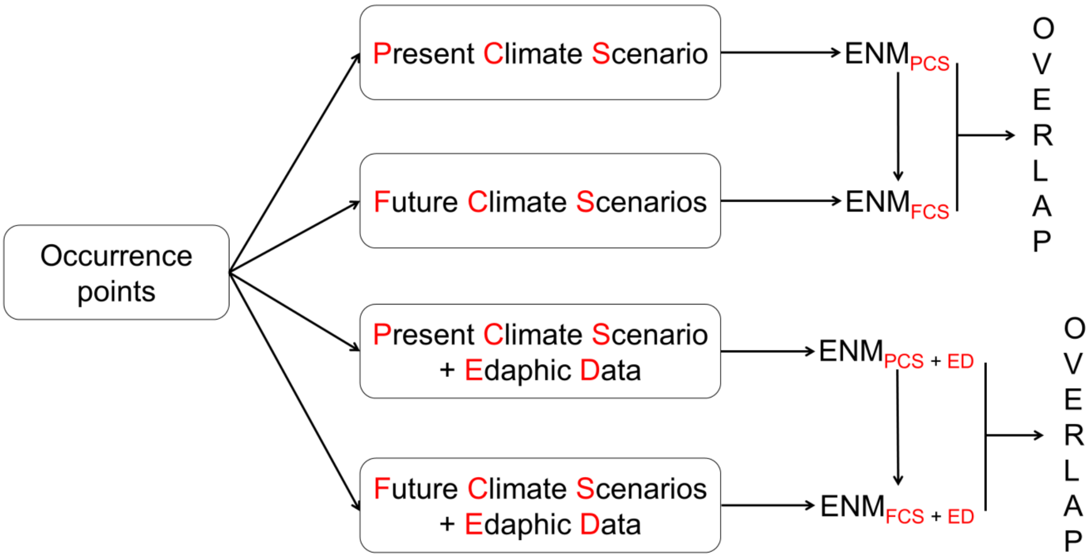

Fig. 1- Experimental design to test the assumption of edaphic effects on plant distribution under different climate change scenarios. All models were done using occurrence points and fitted in present climate scenario (PCS) and projected to future climate scenarios (FCS). The inclusion of edaphic data (ED) in models is expected to produce smaller distributions under future climate. The prediction is that the overlap between future and present distribution will be smaller for models that include ED.

Our response variable was the difference in the proportion of overlapping area of each bat pollinator and the plant distribution with edaphic data for the present and each future climate scenario. This was done for each possible combination of interaction (plant and pollinator 1; plant and pollinator 2; and plant with both pollinators). Present model comprise only one value of overlap area, while future models include several values derived from different climate scenarios. Thereby, we used an inference based on average and confidence interval estimates to evaluate the hypothesis that the overlap among the distributions decrease for future scenarios. Here, we use the confidence interval estimates to evaluate the effect size that was represented by the forest plot analysis (Michael Borenstein, Larry V. Hedges, Julian P. T. Higgins, 2009).We expected that the difference between the present and future to be less than zero.

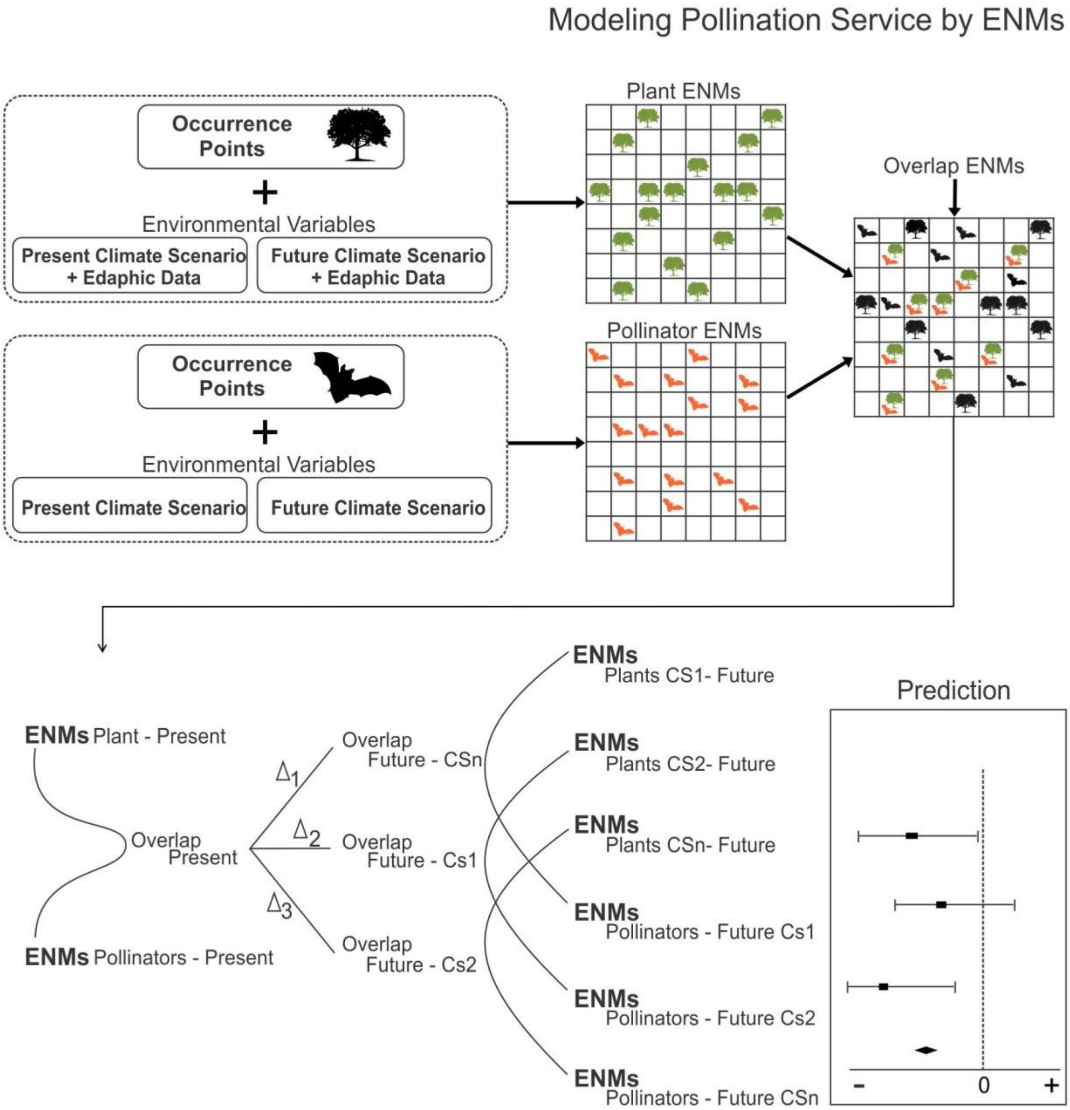

Fig. 2- Experimental design to test the hypothesis that the overlap among the distributions decrease for future scenarios. The ENM procedures for plant use occurrence points and the environmental variables (climate and climate-edaphic data), while for bat pollinators use only climate data. After that, the binary map is generated for all species present in the interaction. Using these maps, we measured the overlap between the plant and bat pollinators for all combinations of interaction (for present and future climate scenarios). Thereby, we obtained the difference value between present and future climate scenarios ($Overlap_{Future}$ - $Overlap_{Present}$), in which the prediction result is that these difference are smaller than zero.

3. Results

We found a small difference in the plants' distributional size when using edaphic data in the ENM. This result supports our assumption that edaphic data constraint plants' distribution. Furthermore, in future scenarios, the spatial distribution of “Pequi” remains significantly the same. On the other hand, the models using climate-only data evidenced more uncertainty on geographic distributional size (Fig. 3). This is because there are less accurate cell predictions in the North of the maps. Nevertheless, the geographic distributional sizes do not change with the combination of edaphic variables and climate data (Fig. 4), but is reduced in future if only climate data is used.

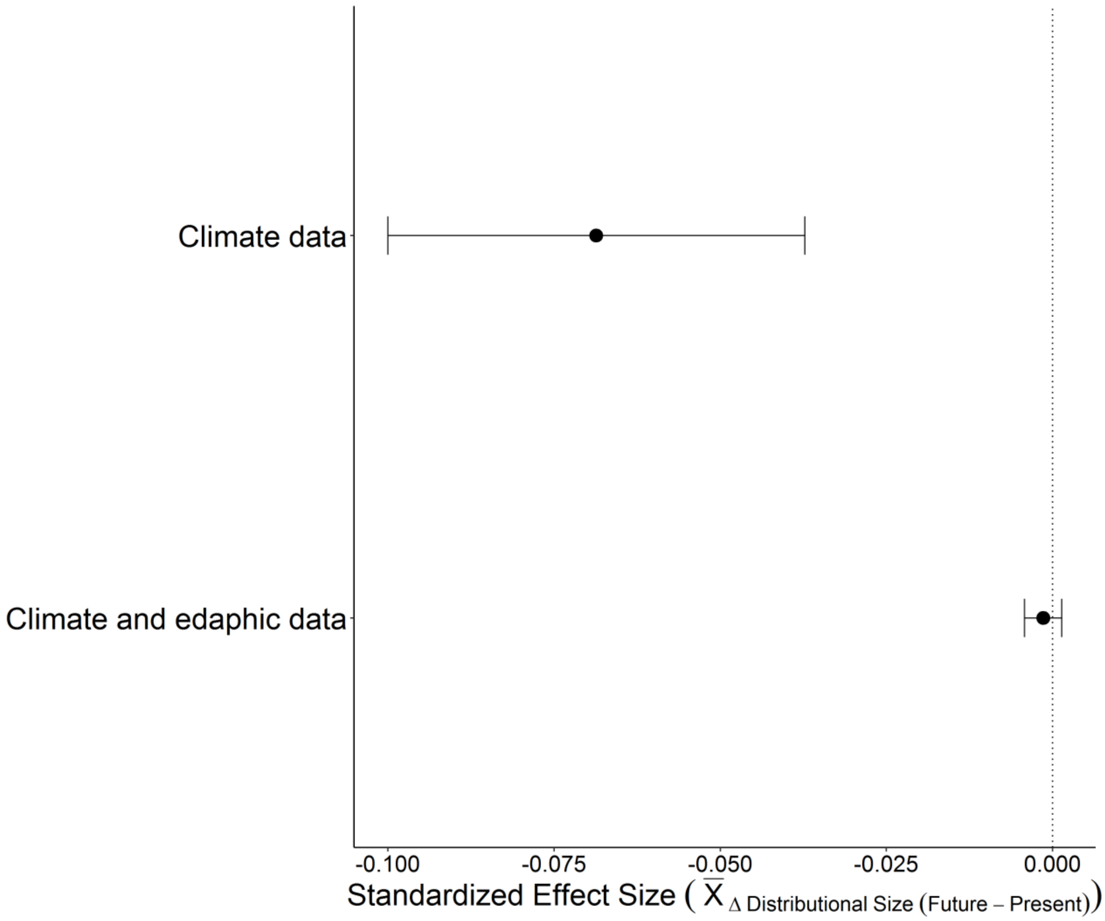

Fig. 3- Forest plot testing the effect of the addition of edaphic data in the plant’s modeling procedures. This analysis was performed using climate-only and with edaphic data added to climate database. Each model was projected for 17 future models. From this, we counted the number of cells for the present and each future model respecting Brazilian borders and calculated the difference between each future model and the present. This result was standardized using the current model of plant distribution.

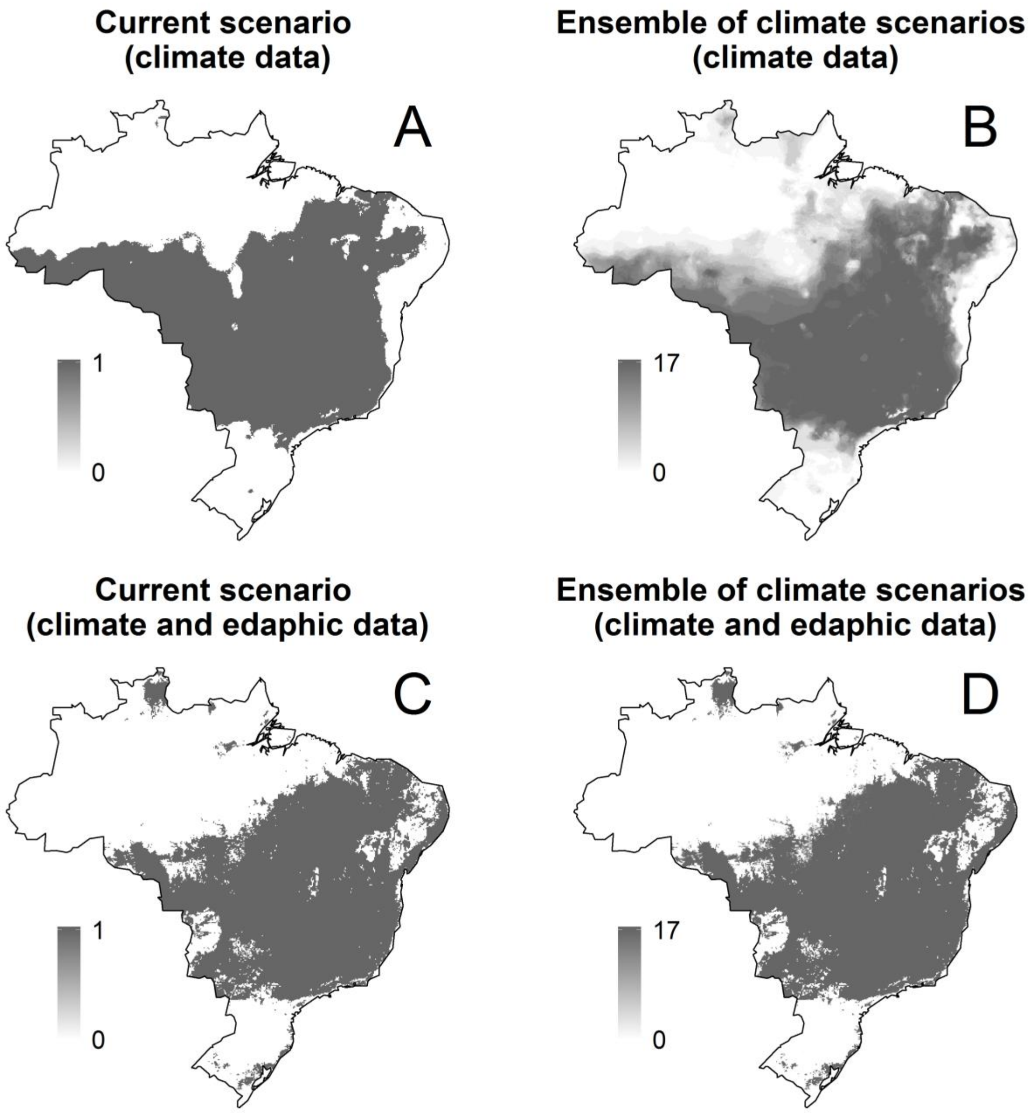

Fig. 4- Spatial distribution using different datasets for the current and future models in the plant modeling.

We also found that the overlapped distribution of bats and "Pequi", as well as their distributional range, do not change in future scenarios, indicating that the pollination service for "Pequi" trees will be maintained (Fig. 5). We observed that *A. geoffroyi* restricts the overlap with "Pequi" distribution. However, the interaction has lower spatial uncertain is *C. brasiliense* and *G. soricina*, maintaining the overall level of overlap with "Pequi" distribution.

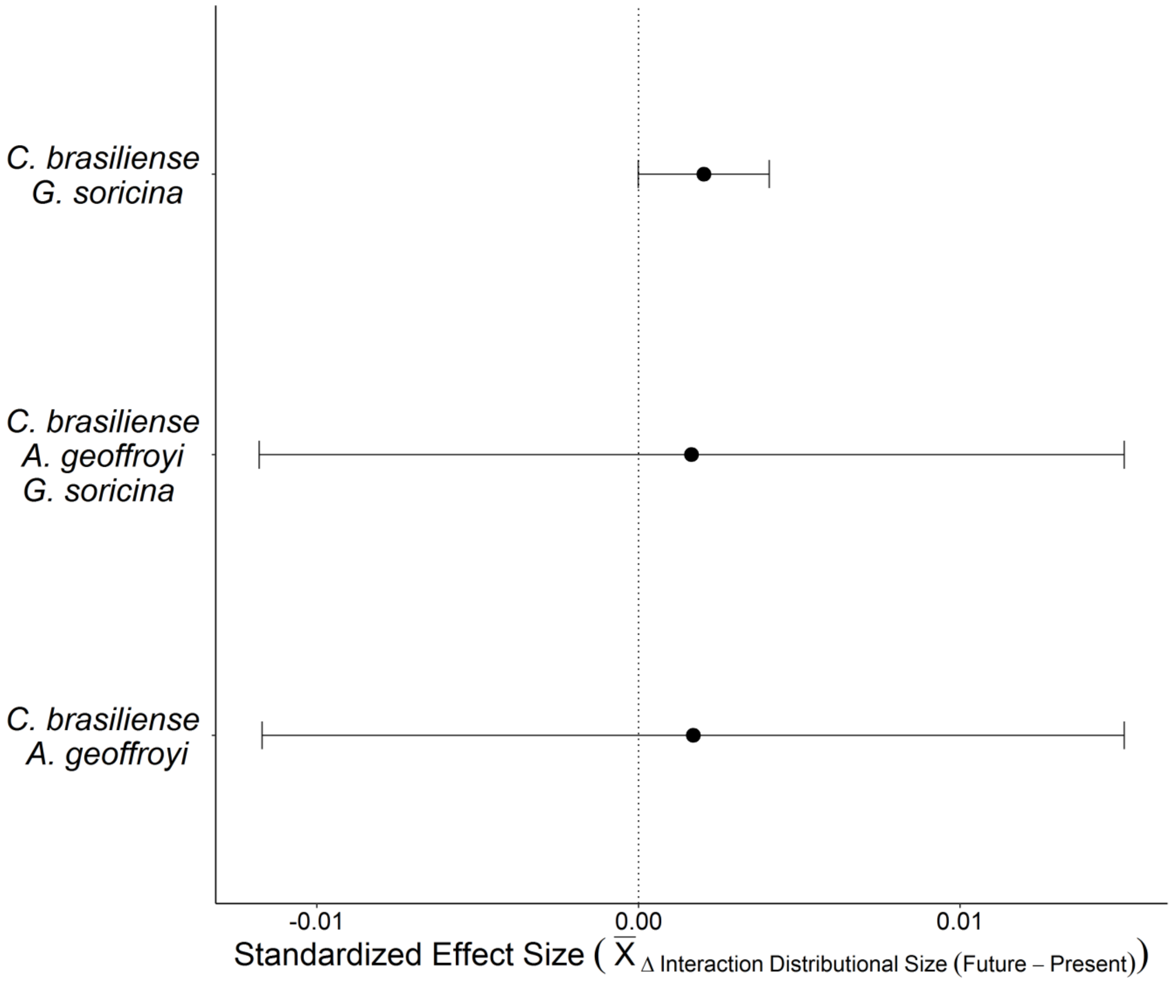

Fig. 5- Forest plot testing if interaction distributional sizes reduce in future scenarios. This analysis was performed using climate and edaphic data for plant modeling and climate-only for pollinators. In this analysis, the geographical distributions of the species were overlapped for present and each future model. From this, the number of cells was counted for the present and each future model respecting the Brazilian borders, and the difference between each future model and the present. This result was standardized using the current model of plant distribution.

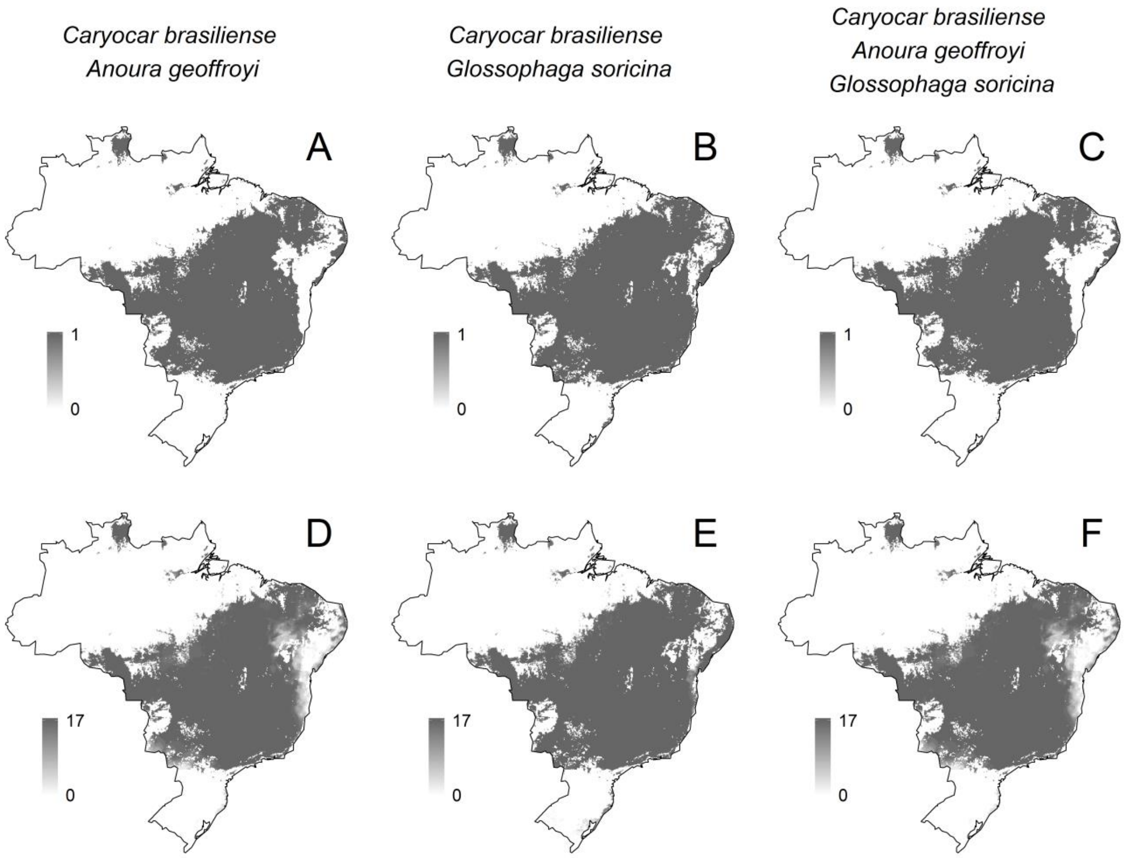

Fig. 6- Overlap between the distributional sizes of all species in three combinations: *C. brasiliense* and *A. geoffroyi*, present (A) and future (D); *C. brasiliense* and *G. soricina*, present (B) and future (E); and *C. brasiliense*, *A. geoffroyi* and *G. soricina*, present (C) and future (F). For each interaction there are 17 future combination models. All procedures were done using edaphic data in the plant modeling.

DISCUSSION

Our results suggest that the use of the edaphic properties may restrict the distribution of plants, indicating that our assumption is true for *C. brasiliense*. Specifically, we observed a small difference between the current and future scenarios when using the association of climatic and edaphic data as predictor variables. This may indicate that the use of edaphic data produces better predictions about plant distributions. In the scientific literature most studies involving ENMs for plants (including *C. brasiliense*) used only climate data as environmental predictors (Gaikwad et al., 2011; Trethowan et al., 2011) (Collevatti et al., 2011b, 2011c; Diniz-Filho et al., 2009; Nabout et al., 2011). In these studies, it is possible to observe that the climatic conditions strongly alter the distribution of “Pequi”, which shifts from the central to the southeast region of Brazil. Nevertheless, some studies have incorporated the edaphic data for modeling plants (Velazco et al., 2017), but did not compare the effect of different environmental predictors in their distributional size. Altogether, our models contrast the results found in the literature.

For *C. brasiliense*, it is possible that its large known distributional size is associated with large climate/edaphic tolerances, which explains both the large predicted current and future distributions. However, we cannot discard the hypothesis that not only environmental conditions but intrinsic demographic characteristics and external landscape structures affect its success in nature. For instance, interspecies and intraspecies competition, and the lack of pollinators may reduce its development. Otherwise, habitat loss may affect all those interactions besides a direct effect on its persistence. Despite this, our models indicate that the addition of edaphic variables for modeling plants with larger distributions, such as *C. brasiliense*, will possibly produce similar distribution under present and future climates scenarios. On the other hand, for species with restricted distribution, additional constrain due to soil will produce even smaller distributions under future climate scenarios Thereby, our results comparing the different environmental predictors in ENM suggest that the use of edaphic data may produce more accurate predictions for the plants, including better future projections (Velazco et al., 2017). Consequently, these variables may contribute with the establishment of priority areas for conservation due better descriptions of species' niche (Velazco et al., 2019).

The analyses of the distributional size of the interaction between plant and pollinators under climate change scenarios suggest that it will not be affected in the future. As discussed earlier, one possible reason for this is the "Pequi" and its pollinators' distributional sizes, both with wide distribution. This condition allows us to say that, regardless of the areas where our ENMs indicate as suitable for this plant, its pollinators will potentially share the same area, because all species are broadly distributed. As a consequence, if the pollination service is the main condition for a high fitness, our results support the idea that *C. brasiliense* maintain its reproductive rates in future scenarios. This result is on the opposite direction of many ecological interactions models for plants and their pollinators under climate change (Jackson and Overpeck, 2000). We strongly suggest that two important points need to be observed in those studies and many need to be reviewed to a better evaluation of the problem. First, is necessary to make a more careful prediction about the importance of future climate change to disconnect the distributions of plants and its pollinators decrease with the increase of the range-sizes of the plant and its pollinators. Secondly, that plant models lacking edaphic information may provide an incomplete understanding of plant distributional patterns and, according to our results, may predict higher differences than expected with better or more complete ENM models.

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Using Ecological Niche Models to predict the potential production on “Pequi” fruits in Brazil

Pablo Henrique da Silva[a,b,]* - Paulo De Marco Júnior[b]

[a] Programa de Pós-Graduação em Recursos Naturais do Cerrado – RENAC, Universidade Estadual de Goiás (UEG). BR 153, Quadra Área, Km 99, Bloco IV, 1ª Andar, 75132-903, Anápolis, Goiás, Brazil.

[b] Theoretical Metacommunity and Landscape Ecology Laboratory, Departamento de Ecologia, Instituto de Ciências Biológicas (ICB), Universidade Federal de Goiás (UFG). Rodovia Goiânia-Nerópolis km 5, Campus II Itatiaia, 74001-970, Goiânia, Goiás, Brazil.

* Corresponding author at: Theory, Metacommunity and Landscape Ecology Lab. Instituto de Ciências Biológicas V, Universidade Federal de Goiás, Goiás, Brasil. 74001-970.

E-mail address: phecosilva@gmail.com (P. H. Silva).

1. Introduction

Worldwide population growth put agriculture productivity as a major human concern (Carvalho, 2006; Ruttan, 2015). Both present-day restrictions and ongoing climate change jeopardize food production because it can alter the spatial distribution of fruitful species and their pollinators, for example (Olesen and Bindi, 2002). In plants, the environmental characteristics such as climate conditions, nutrients availability, pH and other soil properties are the major determinant of their productivity (Poorter and Nagel, 2000). Furthermore, these information are often used in agrometeorological models to identify suitable areas for agriculture (Hoogenboon, 2000), which inform farmers to better chose their investments. On the other hand, spatial models that indicate optimal conditions for crop production may help government agencies to optimize resource investment on agriculture (Matthews et al., 2008). Similarly, knowing the future distribution of suitable areas for crop production may subsidize the creation of strategic plans for the food production (Matthews et al., 2013).

Despite a lot of interest are currently on the most valuable agriculture commodities, such as sugar cane, soybean and corn (Martinelli et al., 2010), many less economically relevant tropical plants may have an important role in future economy. Pequi, tropical palms, Cupuaçu and Açaí, are important fruits of the Netropical realm which are majorly consumed in local markets but with potential to acquire worldwide relevance. Unfortunately, the knowledge on their response to climate and soil is still insipient. To solve the lack of information about the environmental conditions necessary for high plant productivity, some studies have been using the ecological niche theory to map optimum areas for food production (D'Alpoim Guedes and Butler, 2014). According to this theory, ecological niche is a set of environmental conditions necessary for a species to survive in a given location. Niche theory assumes that the environmental conditions required by species do not change through time (Wiens and Graham, 2005). This allows the projection of the current environmental condition to future scenarios, and the identification of possible suitable areas (Blanchard et al., 2015). There are other applications of this theory, such as to determine suitable areas for species and investigate their niche width (Morueta-Holme et al., 2010; Mykrä and Heino, 2017). Particularly, some studies are using suitability maps to estimate other environmental characteristics, as well as abundance of species and its probability of detection in nature (Mendes and De Marco, 2018).

The ENM is a statistic advanced tool used in ecological studies that can predict suitable areas based on a range of environmental tolerance of focal organisms (Guisan and Thuiller, 2005). This method associate occurrence records on geographic space to environmental conditions in which the species live. This association is a proxy for the species' fundamental niche, and is used by the model to estimate the suitability of new areas of occurrence (Kearney and Porter, 2009). Most ENMs are performed using only climate data, but some studies have investigated plant distribution adding edaphic data to the environmental dataset (Velazco et al., 2017; Walthert and Meier, 2017). (Especially) For plants, soil data may improve the fit of the models due to their biological requirements. Therefore, the performance of these models is dependent of the combination of biologically important variables. Because ENMs indicate best suitable areas for a certain species, and we can securely assume that this is reflected in their reproductive success (talvez citação aqui), they can be very useful to predict the productivity of economically important crops (sei lá, frutas, plantas, etc).

The "Pequi" tree (Caryocar brasiliense Camb, Caryocaraceae) has a strong economic impact in many municipalities due to its several uses by society (Guedes et al., 2017). For instance, the "Pequi" fruit may be used directly in the culinary and in the extraction of secondary products, such as oils. It is a broadly distributed species in Brazilian territory, and is pollinated by two nectarivorous bats (*Glossophaga soricina* and *Anoura geoffroyi*) (Gribel and Hay, 1993), also of wide distribution. Based on this, our aim is to test the prediction power of climate and edaphic variables on current fruit productivity of "Pequi" in the Brazilian Cerrado. Specifically, we hypothesize that the addition of edaphic variables to a climate dataset will improve model predictions. We performed Ecological Niche Models using climate with and without edaphic variables to explain the spatial variation in "Pequi" fruit production. Considering the economic importance of this plant, we also evaluated how climate change could affect both the mean productivity and its spatial distribution in Cerrado.

2. Material and methods

2.1. "Pequi" distributional database

We developed our database through a systematic review seeking occurrence records of "Pequi" on the Web of Science and Scopus platforms using the search code ("Caryocar brasiliense" OR "C. brasiliense" OR "pequi" OR "piqui" OR "pequizeiro" OR "piquizeiro").

We complemented the data using the GBIF (https://www.gbif.org/) and SpeciesLink (http://splink.cria.org.br/) distribution databases. To reduce data uncertainties, we applied four quality criteria: latitude and longitude exchange, duplicated records, records outside the Neotropical realm, and occurrence records with possible problems of taxonomic identification. Occurrences were corrected when possible and eliminated otherwise.

2.2. Productivity data

We obtained the “Pequi” fruit production data from the Brazilian Institute of Geography and Statistics (IBGE; www.ibge.gov.br) using the Automatic System Recovery (SIDRA) in the category “Production of Vegetable Extraction and Forestry”. Altogether, we collected the amount of fruits produced in 242 Brazilian Cerrado’s municipalities in 2017. These data contained the amount of fruit produced (in ton) for each municipality, andwe converted it to kilograms. In addition, we calculated the area for all municipalities producing “Pequi” and correlated the fruit production and area.

2.3. Environmental variables

Our environmental database contains two variable types: climate and edaphic. We obtained 19 bioclimatic variables from WorldClim database (http://www.worldclim.org/) for present and future scenarios in a Representative Concentration Pathways 8.5 projected for 2070. We also used 17 future climate models from the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). We obtained the edaphic data from International Soil Reference and Information Centre (ISRIC, https://www.isric.online/) (Hengl et al., 2014)(Hengl et al., 2014) and selected eight variables that we considered important for the Cerrado region: (1) Depth to bedrock (R horizon) up to 200 cm; (2) Probability of occurrence of R horizon; (3) Cation exchange capacity of soil in cmolc/kg; (4) Clay content (0-2 micrometer) mass fraction in %; (5) Soil pH x 10 in H_2O; (6) Soil pH x 10 in KCl; (7) Silt content (2-50 micro meter) mass fraction in %; and (8) Sand content (50-2000 micro meter) mass fraction in %. We obtained the edaphic data in a spatial resolution of 250 meters and upscaled them to 5 arc-minutes (≈10 km cell size), in a similar resolution to the climate data. For this, we used the average value of the cells in higher resolution. In general, we separated these variables in two datasets: (1) climate-only (hereafter climate data); (2) climate and edaphic together (hereafter environmental data). For each dataset, we performed a Principal Component Analysis (PCA) to reduce the multicollinearity (De Marco and Nóbrega, 2018), decreasing the complexity of the ENM algorithms. Then, we select the axes in which the sum represents at least 95% of the total variation of the data.

2.4. Ecological Niche Modeling (ENMs)

The ENM is a statistical procedure used in several types of studies, as well as potential distributions (Gallien et al., 2010), and how species respond to climate change (Walther et al., 2002). Here, we proposed the use of this method to estimate the potential fruit production of “Pequi” through of the estimated model between the productivity and suitability for each municipalities of the Brazil. As most of current and future distribution of this species are in the Brazilian Cerrado (see Chapter 1), this specially represent this biome that is considered the origin of the distribution of this species. The ENM procedures relate the species’ occurrence records to environmental variables, in order to estimate the environmental suitability. We chose five modeling algorithms to perform this analysis: (1) Maximum Entropy (MXS) (Phillips et al., 2017, 2004); (2) Random Forest (RDF) (Prasad et al., 2006); (3) Support Vector Machine (SVM) (Guo et al., 2005); (4) Maximum Likelihood (MLK) (Royle et al., 2012); e (5) Gaussian (GAU) (Golding and Purse, 2016). Some of these algorithms require absence data to fit the models. In those cases, we generated pseudo-absences in areas environmentally dissimilar to known occurrence points to avoid misplace of absences in areas with high probability of species occurrence. To accomplish that, we produced a simple initial distribution model using the BIOCLIM (Busby, 1991) and only chose pseudo-absences outside those predicted areas around the real points.

Two important steps are required to check how well the algorithms were successful. First, we separate the dataset into two equal-size training and testing data applying a spatial partition that subdivides the geographic extent into a checkerboard pattern, which controls the effects of spatial autocorrelation on the independency of the training and test dataset (Muscarella et al., 2014). The size of the checkerboard cells are chosen as to minimize spatial autocorrelation, by the I-Moran, and maximize model transferability, measured by the environmental similarity between the datasets using the multivariate environmental similarity surface (MESS). Second, we estimate the algorithms performance through the True Skill Statistics (TSS, TSS = sensitivity + specificity – 1). This procedure is considered simple and intuitive in the evaluation of ENMs’ performance (Allouche et al., 2006). . Otherwise

To reduce the errors associated with each algorithm, we produced consensus maps to summarize the geographic information in a single layer. Despite of several ensemble methods listed in the literature (Marmion et al., 2009), we opted to use only the mean of a subset of algorithms with high adjust(ed?) value (> overall mean TSS) , for both present and future scenarios. All procedures were performed using ENM_TheMetaLand package in software R (https://github.com/andrefaa/ENM_TheMetaLand).

2.5. Analytical procedures

There are some studies discussing the relation of the predictions of ENM and population parameters, such as abundance (Tôrres et al., 2012; VanDerWal et al., 2009). Those studies emphasize the theoretical expectation that the ENM may represent constrains on the maximum values of the parameter, not its mean values. In fact, environmental suitability may control for the maximum expected yield for the plant under the best conditions, but many other factor affect the observed values such as competition, pests, etc. Thus, we applied a quantile regression to estimate the relation of different quartiles in interpret this theoretical possibility. In order to test the relationship between the plant's productivity and suitability, we performed quantile regressions for each environmental dataset. This regression is often used by ecologists due the possibility of finding better relations between variables (Cade and Noon, 2003). Furthermore, the quantile regression presents better fit for outliers. Additionally, we performed ordinary least square regressions to describe a general model for these relationships.

In order to describe the geographic pattern of "Pequi" productivity, we used municipality as our sampling unit. Thus, we used the average suitability derived from both climates only and climate-soil ensembles of each municipality as our predictor in both quantile and the common Ordinary Least Square (OLS) procedures. We applied quantile regressions at 5%, 50%, 90% and 95% quantiles. To linearize the relation we applied a logit transformation ($ln\left(\frac{x}{1-x}\right)$) on the suitability values and productivity data.

3. Results

We found that the edaphic data better explained the "Pequi" productivity (Fig. 1a, 1b). Edaphic data improved the model fit compared to those with climate-only data (Table 1). The overall triangular distribution of data supports the use of the quantile regression. Specifically, there was statistically significant relation for the 90% quantile, suggesting that maximum productivity of “Pequi” fruits are related to suitability estimate using climate and edaphic data (Pseudo $R^2 = 0.084$; $p < 0.001$) (Table 1). However, no regressions had a strong explanation between data. Furthermore, no regressions using climate-only data for the suitability were significant (Table 1).

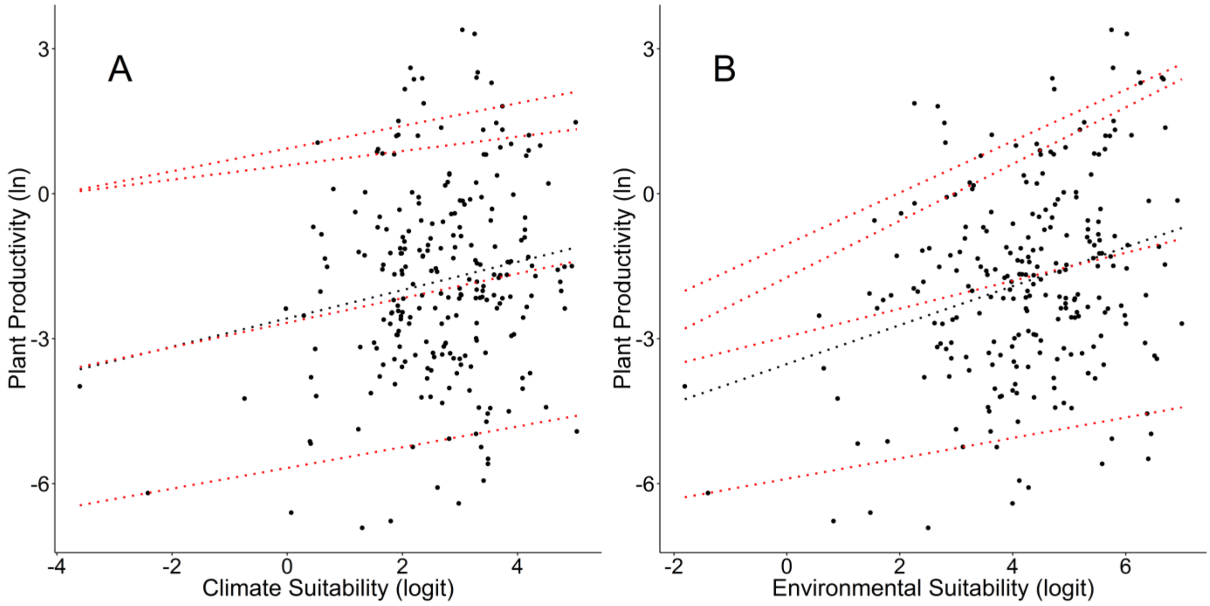

Fig. 1- Quantile (red lines) and ordinary least square regression (black lines) between “Pequi” fruit production and suitability predicted by climate-only (A) and climate+edaphic data (B). Both regressions were made with quantiles 0.05, 0.5, 0.9 and 0.95.

Despite the low fit of regressions, we used the quantile regression of 0.9 to estimate the productivity due its significant result and the greatest fit between data. We observed a small difference between the current and future models: there is a retraction of the high productivity areas, in which some municipalities will lose favorable environmental conditions for good fruit production in the future (Fig. 2). However, the geographic pattern of the “Pequi’s” productivity doesn’t change, being that the most central municipalities will remain with high values for fruit production. In addition, the distribution of productivity seems to be concentrated within the limits of the Cerrado biome. A special highlight is the existence of a prediction for “Pequi” trees in areas of Roraima (Northern region of Brazil), where it is known to occur vegetation similar to Cerrado.

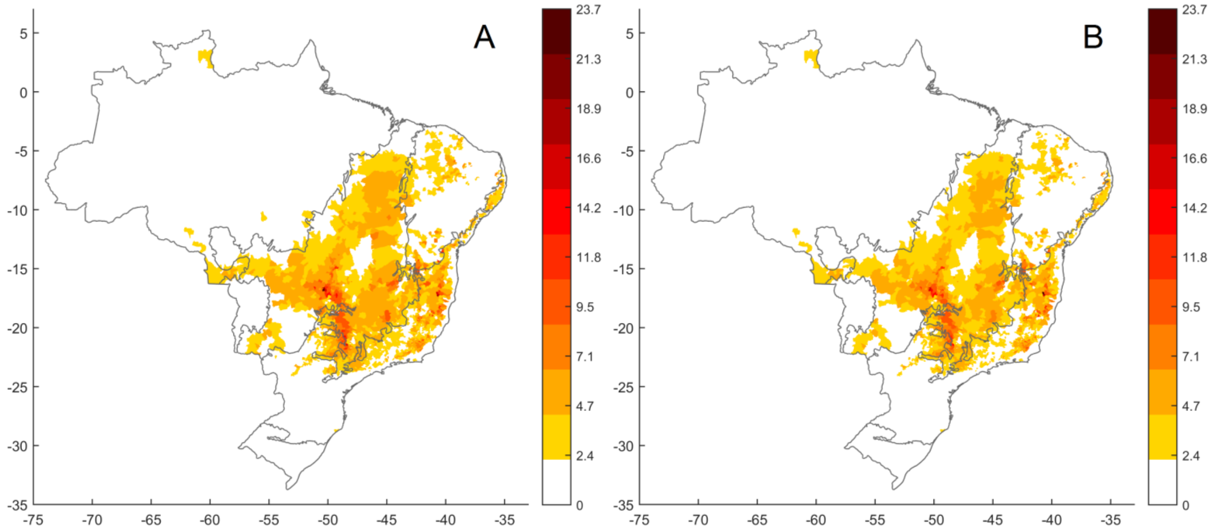

Fig. 2- Productivity maps of "Pequi" fruits for current (A) and future scenario (B). These maps were constructed using the Brazilian municipalities as sample unit. For each municipality the average suitability was calculated using the environmental dataset with addition of edaphic data. Then, environmental suitability was used to estimate the maximum yield fruit production. This was done using the parameters of the quantile regression of 90%.

4. Discussion

Our results suggest that the models created by the association between climate and edaphic data better explains "Pequi" productivity. In addition, this environmental dataset improves the fit of the models mainly for the high fruit production. This result may mean that the addition of edaphic data also improves the known tolerance range, approximating of the species' realized niche. The realized niche may be considered as accessible geographic areas where the environmental conditions are favorable for the persistence of species (Vetaas, 2002).In this case, if edaphic data better describes the realized niche, is possible that, for plant species, this type of environmental dataset may indicate more accurate suitability areas. In addition, we found that the spatial distribution of productivity suffers a small contraction for core areas of the Cerrado biome, indicating a small reduce of fruit production in future scenarios. From this result, we may say that the "Pequi" tree will adapt to climate changes, presenting a potential use by the Brazilian economy.

Theoretically, niche responses may determine the maximum fitness of individuals rather than its observed mean values (VanDerWal et al., 2009). We could consider that ecophysiological constraint on plants may determine its maximum yield under determined edaphic and climatic conditions. However, no single plant must remain under these edge conditions. In fact, real plants lose part of its fitness due to a large range of possible demographic phenomena. For instance, intra-specific and inter-specific competitions are among the most suggested causes for this kind of loss. To exemplify this, distance between plants in forestry plots explain a large amount of productivity variance in a demographic phenomenon called self-thinning (Weller, 1987). Otherwise, other biological characteristics also may affect the fitness in plants. For instance, the availability of pollinators may reduce the fitness mainly in species which the self-pollination rate is low. For instance, the "Pequi" tree presents low self-pollination, depending strongly of pollinator for its reproductive rate (Gribel and Hay, 1993). Also, the presence of agricultural pests may be one of responsible factors for the low productivity in several crops. All those aspects considered small predictive power for an OLS model of mean productivity is highly expected. Otherwise, control of productivity under strict management practices (distance between plants, pest control and soil corrections) may provide productivity estimates closer to the maximum yield expected under an ecophysiological model. Unfortunately, this information is not currently available for the majority of crops, including the Pequi. Considering that the available information (used in this study) was mean productivity at the municipality level, our predictive power and observed relations should be considered as good.

"Pequi" productivity distribution had a minor general change from present to future climate scenarios. Although this result points to a different direction than the majority of studies in this field (Collevatti et al., 2012, 2011; Nabout et al., 2011), it may have a strong theoretical support. For example, it is expected that species with large current geographic distributions, such as Pequi, have developed ecophysiological responses for different climates. Thus, they are naturally adapted to climate changes, at least to a certain degree. Otherwise, our results show that the expectation of large changes in some studies may result from the incomplete access to plant ecological requirements by only including climate variables into the analysis. Our models including edaphic properties, which display only minor changes under future climate scenarios, represent a better description of "Pequi" production for the current scenario. The inclusion of soil variables in ENM studies has long been suggested in plant studies but only recently the existence of worldwide soil grids and a detailed evaluation of its use (Velazco et al., 2017) made this more effective. These are the main reasons to explain the differences between our results and the similar study of Nabout et al. (2011), which only used climate data to model "Pequi" distribution and found a large change in future climates, especially in the southeastern area. Our study does not support the existence of those large effects, mainly due to the stabilizing effect of the soil constraining plant distribution (see chapter 1 results). Those results also suggest the need to revise other similar studies to include soil variables to better understand the real climate change effects on plant species distribution.

Our results about the spatial predictions indicate that main municipalities for maximum “Pequi” production are distributed within the limits of the Cerrado biome. In addition, in future scenarios it is expected only a retraction on distribution of municipalities with high potential of fruit production, indicating that “Pequi” tree presents no evident threats under conditions of future climate changes. This may imply that the “Pequi” fruit production has a potentially profitable market in Brazilian forestry.

The most important strategy to deal with ongoing climate change is to adapt (Adger et al., 2005). Most of international programs try to find ways to adapt our current economy and well-being to inexorable climate change consequences. The existences of some crops that are expected to not change under climate change scenarios are one of those strategies. Here, we show that “Pequi” productivity satisfy this criteria. Currently, the consumption of “Pequi” is restricted to parts of the central region of Brazil and some parts of the northeastern areas. Otherwise, popularization of its use could be easily developed in a convenient time-frame. This exercise highlights the importance to seek for other possible native plants with similar responses as potential crops to invest in Brazilian climate adaptation programs.

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CONSIDERAÇÕES FINAIS

Os resultados derivados da Modelagem de Nicho Ecológico indicam que o serviço de polinização em Pequi não será fortemente afetado, pois as espécies envolvidas nessa interação possuem amplas distribuições geográficas e dificilmente haverá uma incompatibilidade espacial em cenários de mudanças climáticas. Da mesma forma, poucos municípios produtores de Pequi perderão a sua produtividade como consequência das mudanças climáticas. Isso pode indicar que essa espécie de planta é uma ótima alternativa para manter a economia de alguns municípios do Cerrado brasileiro, bem como uma fonte de recurso alimentar para a população local. Assim, esse tipo de cultivo pode ser considerado uma forte alternativa de segurança alimentar ao longo do tempo pela possibilidade de se manter em crises climáticas.