Universidade de Brasília (UnB)

Centro de Desenvolvimento Sustentável (CDS)

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FELIPE DEODATO DA SILVA E SILVA

DESAFIOS PARA O USO SUSTENTÁVEL DA POLINIZAÇÃO NA AGRICULTURA: ameaças da intensificação agrícola nos benefícios socioeconômicos da polinização

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Orientador: Prof. Drº Frédéric Mertens (CDS/UnB)

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RELATÓRIO DE DEFESA DE TESE

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3 - Comissão Examinadora

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Resumo

Alimentar a crescente população global sem comprometer o funcionamento dos ecossistemas e a biodiversidade é um dos grandes desafios da agricultura. A polinização agrícola é um serviço ecossistêmico importante para a produção de alimentos e que está ameaçado pelo próprio sistema produtivo agrícola. Partindo dos conhecimentos das ciências da natureza, este pesquisa explora essa problemática pela perspectiva socioeconômica e em diferentes níveis de análise focando no benefício econômico desse serviço, nos custos associados ao seu manejo e nas estratégias de proteção aos polinizadores. O questionamento central desta tese é compreender, em diversos níveis, quais são os benefícios socioeconômicos associados aos serviços de polinização agrícola? O tema foi abordado em três níveis espaciais de análise: local, da paisagem e nacional/global. O estudo no nível local avaliou como o manejo agrícola convencional afeta os benefícios econômicos que os produtores recebem dos polinizadores. Para isso, utilizou-se de um modelo baseado na função de produção que foi aplicado na polinização do feijão comum (*Phaseolus vulgaris L.*), produzido em fazendas do Distrito Federal e Goiás, Brasil. Os resultados demonstram que a aplicação de práticas que aumenta a abundância de polinizadores nativos juntamente com o uso eficiente de fertilizantes é mais rentável ao produtor do que a intensificação agrícola convencional. Em seguida, o estudo no nível da paisagem avaliou como a atual política brasileira de conservação da natureza pode beneficiar economicamente o produtor por meio dos serviços de polinização. O estudo focou em sistemas agrícolas de feijão localizados em regiões regidas pelo Código Florestal Brasileiro. Os resultados mostram que, os polinizadores nativos associados à potenciais áreas de Reserva Legal beneficiam economicamente os produtores mesmo na ausência de instrumentos econômicos que estimulam a conservação da natureza. Por fim, o estudo avaliou como o comércio internacional de produtos agrícolas dependentes de polinizadores está expandindo a área agrícola pelo mundo (nível nacional/global). Usando dados de 52 culturas para 115 países durante 1993 e 2015, os resultados mostram que, para atender o seu consumo interno, os países mais desenvolvidos demandam intensamente os serviços de polinização (i.e., fluxo virtual de polinização) dos países menos desenvolvidos. Consequentemente, esse comércio é um dos principais causadores da expansão das áreas agrícolas nos países exportadores. Com base em todos os resultados deste estudo, pode-se concluir que para a proteção dos polinizadores é necessária uma ação coordenada entre diferentes tomadores de decisões que atuam em diversos níveis.

Palavras-chaves: Polinização agrícola, intensificação ecológica, valoração de polinizadores, conservação da natureza, fluxo virtual de polinização.

Abstract

To feed a growing global population with no depletion in ecosystem and biodiversity is a great challenge for agriculture. Crop pollination is an important ecosystem service for food production that is under threat due to crop systems. This thesis aims to explore such issue using a socioeconomic perspective and a multi-level approach focusing on economic benefit of this service, on its associated cost of management, and on strategies to protect pollinators. The main question of this thesis is to understand what are the socioeconomic benefits associated to crop pollination services at different levels of analysis? The approach was based on three spatial levels of analyze: local, landscape, and national/global. The study at local level assessed how conventional management affects the economic benefits that farmers receive from pollinators. A production function based model was applied on pollination of common bean production (*Phaseolus vulgaris L.*) located at central Brazil. Results showed that the application of practices that increase the abundance of native pollinators in addition to efficient use of fertilizer is more profitable to farmers than conventional agricultural intensification. Secondly, the study at landscape level assessed how current Brazilian nature conservation policies affect farmers' profitability via pollination services. The focus was on crop system of common bean ruled by Brazilian Forest Code. Results showed that native pollinators associated to potential areas of Legal Reserve bring economic output for farmers even in the absence of economic instruments to stimulate nature conservation. Lastly, the study assessed how international trade of pollinator-dependent crops is expanding cropland areas worldwide (national/global level). Using data on 52 crops in 115 countries over 1993-2015, the results showed that, to meet domestic consumption, most developed countries intensively demand pollination services (i.e., virtual flow of pollination) from less developed countries. Consequently, this trade is one of the main drivers of cropland expansion in exporting countries. Taking into account those results, I conclude that to protect pollinators is required coordinated actions between stakeholders that act in several spatial levels.

Key-words: crop pollination, ecological intensification, crop pollination valuation, nature conservation, virtual flow of pollination.

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Sumário

INTRODUÇÃO GERAL

Nas últimas décadas, a sociedade integrou de forma crescente a dimensão ambiental nas estratégias de desenvolvimento, reconhecendo os limites e os benefícios sociais e econômicos da natureza. Por volta da década de 1970, o debate sobre a degradação dos sistemas naturais ganhou escala global com a Conferência das Nações Unidas sobre o Meio Ambiente Humano. Inicialmente, a preocupação política girava em torno de temas polêmicos, tais como, a poluição do ar e dos recursos hídricos, buraco na camada de ozônio, impactos com a energia nuclear, aquecimento global, entre outros. A partir da década de 1990, intensificou-se a preocupação com a biodiversidade dos ecossistemas e a importância dos seus serviços, especialmente, com a criação de Convenção sobre Diversidade Biológica (CDB) durante a Conferência sobre Meio Ambiente e Desenvolvimento da Organização das Nações Unidas, realizada no Rio de Janeiro em 1992.

A biodiversidade foi um termo usado por Edward O. Wilson no final dos anos 1980 para se referir à variedade de vida nos ecossistemas, de espécies e da informação genética (VEIGA e EHLERS, 2010). A biodiversidade contribui para diversos serviços ecossistêmicos (e.g., polinização agrícola, controle biológico de pragas, entre outros) que consistem em fluxos de serviços decorrentes de processos e funções nos ecossistemas que, por fim, beneficiam, direta ou indiretamente, a população humana, estando ela consciente disso ou não (e.g., produção de alimentos) (COSTANZA et al., 1997 e 2017; GROOT et al., 2002; KLEIN et al., 2007; STEWARD et al., 2014). Em 1997, um estudo pioneiro, embora controverso, estimou o valor econômico global dos serviços ecossistêmicos em no mínimo 33 trilhões de dólares por ano (COSTANZA et al., 1997). Por outro lado, segundo a Avaliação Ecossistêmica do Milênio (MEA, 2005), grande parte desses serviços está ameaçada, principalmente, devido às atividades antrópicas associadas à agricultura (e.g., destruição de habitats naturais, introdução de espécies exóticas, homogeneização de paisagens, uso intensivo de insumos químicos, entre outros).

Considerando que os produtos agrícolas são vitais para a humanidade, a proteção da biodiversidade ainda é um grande desafio.

Um valioso serviço ecossistêmico dependente da biodiversidade é a polinização agrícola que contribui para a produção de diversos cultivos agrícolas importantes para a segurança alimentar humana (NABAN e BUCHMANN, 1997; MEA, 2003 e 2005). A polinização é realizada principalmente pelos insetos que, ao coletar os recursos florais, contribuem para a transferência de pólen entre as flores, resultando em sua fecundação e, portanto, na produção de frutas, legumes e sementes em diversos cultivos agrícolas (e.g., maçã, limão, melancia, melão, tomate, soja, feijão, abóbora, entre outros) (KLEIN et al., 2007). Embora existam plantas que se reproduzem por meio da autopolinização, a polinização cruzada é importante para a manutenção da diversidade genética (VRANCKX et al., 2011). Além disso, cerca de 90% das plantas dependem de fatores bióticos (i.e., insetos, pássaros ou mamíferos) para a troca genética entre os indivíduos (OLLERTON et al., 2011; BAUER, 2014).

Os benefícios dos polinizadores para a agricultura são diversos e envolvem desde o aumento na produtividade, mencionado acima, até o melhoramento da qualidade de 39 das 57 maiores culturas agrícola no mundo (e.g., soja, feijão, maçã, tomate, coco, cacau, maracujá, café, melancia, entre outras) (ROUBIK, 1995; KLEIN et al., 2007). Por exemplo, a má fecundação das flores de algumas frutas, tais como a maçã e o morango, resulta em frutos pequenos e mal formados (GARRATT et al., 2014; KLATT et al., 2014). Outro exemplo é a soja, uma cultura amplamente cultivada, cuja produtividade pode ser aumentada em até 18% com os serviços de polinização (MILFONT et al., 2013). Portanto, este é um serviço importante para a produção agrícola com efeitos benéficos tanto para a formação da renda do produtor quanto para o consumo humano.

A polinização também é um serviço importante para a segurança alimentar humana. Embora seja expressivo o consumo dos produtos agrícolas não dependentes de polinizadores (GHAZOUL, 2005), a diversificação no consumo de nutrientes depende em grande parte de culturas dependentes de polinizadores (SMITH et al., 2015; ELLIS et al., 2015). Esse serviço ecossistêmico também é importante para a produção de sementes daquelas culturas que não dependem de polinizadores para a produção de suas partes comestíveis (e.g., milho, arroz, mandioca, cenoura, batata, entre outras) (STEFAN-DEWENTER et al., 2005). Dessa forma, esse serviço é importante para manter a estabilidade da produção (GARIBALDI et al., 2011a) e, consequentemente, da oferta desses alimentos no mercado.

Embora a polinização agrícola seja de grande relevância, há registros do declínio de insetos polinizadores ao redor do mundo. Inicialmente o uso intenso de insumos químicos foi considerado a principal ameaça aos insetos polinizadores. O livro “Primavera Silenciosa” de Rachel Carson, de 1962, trouxe a discussão sobre os impactos dos pesticidas para o âmbito político e cultural destacando seus efeitos sobre os polinizadores, “(...). As macieiras estavam florescendo, mas não havia abelhas zumbindo ao redor das flores, portanto não havia polinização, e não haveria frutos.“ (CARSON, p. 21, 2010). Além do uso de pesticidas, outros fatores também foram apontados como grandes ameaças aos polinizadores, tais como uso intensivo de fertilizantes químicos, extensas áreas de cultivo nos sistemas agrícolas, aparecimento de doenças, introdução de espécies exóticas e mudança climática (MEMMOTT et al., 2007; RICKETTS et al., 2008; POTTS et al., 2010; GARIBALDI et al., 2011b). Tais efeitos são facilmente percebidos em paisagens degradadas com várias áreas isoladas, porém eles também ocorrem mesmo em regiões mais ricas em biodiversidade (CARVALHEIRO et al., 2010). Por outro lado, em sistemas agrícolas menos agressivos, tais como aqueles que preservam áreas de vegetação e otimizam o uso de insumos químicos, a oferta desse serviço é mais abundante (HOLZSCHUH et al., 2008; GARIBALDI et al., 2016b). Uma alternativa então é reduzir o nível de intensificação da agricultura (i.e., reduzir insumos químicos e o nível de desmatamento) e adotar um manejo agrícola menos prejudicial aos polinizadores.

No entanto, não são somente os polinizadores selvagens que estão em risco. Um fenômeno denominado distúrbio do colapso das colônias (DCC ou *Colony Collpase Disroder* – CCD) ocorreu nos EUA em 2006 e consistiu em um grande número de abelhas do mel (*Apis mellifera*) desaparecidas de suas colônias ou encontradas mortas (RUCKER et al., 2016). Suas colmeias eram usadas para polinizar campos agrícolas, tais como amêndoa e maça, e por isso, eram transportadas por todo território norte americano. Até o momento não há um consenso sobre o que gerou desse distúrbio, mas possíveis causas envolvem o ataque de ácaros parasitas (*Varroa destructor* e *Acarapis woodi*), má-nutrição das abelhas decorrente de secas e perda de habitats, elevado estresse devido ao transporte das colmeias, toxinas e pesticidas (RUCKER et al., 2016).

A escassez nos serviços de polinização acarreta na agricultura o déficit de polinização. Esse déficit consiste na diferença entre o máximo potencial produtivo de uma planta e o seu nível atual de produção resultante da ação dos polinizadores, considerando todos os demais fatores produtivos disponíveis em níveis adequados para a produção (VAISSIÈRE et al., 2011). Dependendo da escala em que ocorrem, os impactos negativos podem reduzir a produção no campo agrícola (POTTS et al., 2010; GARIBALDI et al., 2011a). Tais efeitos negativos repercutem na lucratividade de produtor e na disponibilidade de alimentos para o consumidor. As causas do declínio de polinizadores tem sido amplamente pesquisada e debatida por pesquisadores das ciências da natureza (RICKETTS et al., 2008; POTTS et al., 2010 e 2016; GARIBALDI et al., 2011a). No entanto, a perspectiva socioeconômica desse processo ainda permanece superficialmente estudada (mas veja, GARIBALDI et al., 2016a; BREEZE et al., 2016; HIPÓLITO et al., 2016). O que se sabe até o momento é que os déficits de polinização poderão ser particularmente acentuados para os pequenos agricultores (GARIBALDI et al., 2016a), que geralmente abastecem os mercados locais ou produzem para o autoconsumo (HEIN, 2009). No entanto, diversas iniciativas e recomendações foram realizadas para proteger os polinizadores.

1. Proteção aos polinizadores

A particularidade da dimensão socioeconômica está ligada ao modo como as populações humanas são afetadas e como elas poderão reagir aos impactos ambientais, por exemplo, no caso deste estudo, o declínio de polinizadores. Por iniciativa dos brasileiros, a temática de polinizadores foi discutida pela CDB em 1996. Em seguida, em 1998, foi realizado um workshop no Brasil (*Conservation and Sustainable Use of Pollinators in Agriculture, with Emphasis on Bees*) para estudar uma estratégia global de proteção e uso sustentável dos polinizadores que resultou na “Declaração de São Paulo sobre Polinizadores” (DIAS et al., 1999). Essa declaração foi aprovada na V Conferências das Partes da CDB (COP5) em 2000, quando então foi criada a Iniciativa Internacional dos Polinizadores (IPI) (IMPERATRIZ-FONSECA et al., 2012). Assim, diversas iniciativas de proteção aos polinizadores foram estabelecidas ao redor do mundo (Europa, América do Norte, Brasil, África, Oceania, entre outros), incluindo um projeto global de pesquisa financiada pela *Global Environmental Facility* (GEF) que resultou em diversos artigos publicados por revistas científicas de alto impacto e relatórios para a Organização das Nações Unidas para Alimentação e Agricultura (FAO-UN).

Com base nesse conhecimento gerado, diversas recomendações foram realizadas especificamente para a gestão ambiental desse serviço ecossistêmico, envolvendo ações do poder público, do setor produtivo e da sociedade civil (POTTS et al., 2016). Mais recentemente, tais ações envolvem a definição de padrões de regulação de pesticidas, o fornecimento de subsídios aos produtores para adotarem práticas amigáveis aos polinizadores, o reconhecimento da polinização como um insumo agrícola, a conservação e a restauração de áreas de vegetação nativa, o controle do comércio de abelhas, entre outras (DICKS et al., 2016; POTTS et al., 2016). Contudo, a implementação de tais mudanças permanece um desafio para as políticas ambientais, pois depende da capacidade de atuação dos diversos tomadores de decisão. Por exemplo, no nível local da propriedade rural, os produtores rurais possuem maior importância na proteção dos polinizadores, porém sua capacidade de atuação é limitada pela viabilidade econômica de sua produção agrícola. Outro exemplo, num nível mais elevado de atuação, se refere os países que possuem uma heterogeneidade em sua capacidade para definir regulações nacionais e internacionais para a proteção e uso sustentável dos polinizadores. Para avançar os impactos associados ao declínio de polinizadores, em termos socioeconômicos, é necessário compreender as diversas abordagens de valoração econômica desse serviço ecossistêmico e como elas podem contribuir para as estratégias adotadas pelos tomadores de decisão para a conservação dos ecossistemas.

2. A valoração da polinização agrícola

Os ecossistemas oferecem uma série de serviços que beneficiam o bem-estar humano de forma direta (e.g., provisão de água, de alimentos, atividades de contemplação, entre outros) ou indiretamente (e.g., serviços que regulam a produção de alimentos, tais como, a polinização agrícola e o controle biológico de pragas). O valor econômico dos ativos ambientais tem sido analisado conforme seus diversos componentes (i.e., valor direto, valor indireto, valor de opção e de existência) que juntos somam o Valor Econômico Total (*Total Economic Value* – TEV) (PEARCE, 1992). Segundo Pearce (1992), esses componentes representam: o valor direto referente à apropriação de um recurso ou serviço (e.g., os produtos que as abelhas produzem, tais como, mel e própolis); o valor indireto associado às funções ecológicas (e.g., serviços de polinização na agricultura); o valor de opção que a sociedade está disposta a pagar para conservar um determinado ecossistema, ou seja, preservando-o para o uso das gerações futuras; e por fim, o valor de existência que é a vontade de conservar um ecossistema ou uma espécie independentemente de seu uso atual ou futuro.

Embora o valor econômico total possa representar toda a importância de um ativo ambiental para a sociedade, o componente de valor indireto é o mais adequado para orientar o manejo e uso sustentável da polinização pela agricultura. O reconhecimento do valor desse serviço em termos do ganho de produtividade e de qualidade nos cultivos agrícolas pode auxiliar na definição das mais apropriadas de estratégias para a conservação dos ecossistemas. Como se trata de produtos destinados aos diversos mercados (i.e., local, nacional e internacional), a valoração econômica desse componente também é abordada em múltiplos níveis, desde a propriedade rural até o valor da produção agrícola nos países e no mundo.

Um estudo apresentou uma revisão das abordagens metodológicas de valoração da polinização agrícola que são mais adequadas para cada nível espacial de análise (i.e., local, nacional e global) (Hein, 2009). Na escala local, esse serviço beneficia diretamente a formação de renda do produtor rural. Por exemplo, entre 2000 a 2003, um estudo de caso na Costa Rica valorou a polinização em aproximadamente US$ 62.000,00 por ano (cerca de 7% da renda total do produtor no período) em média para uma propriedade rural produtora de café (RICKETTS et al., 2004). Outro exemplo foi um estudo realizado em Minas Gerais estimou o valor da polinização no maracujá em R$ 14.686,02 por hectare no triênio de 2007 a 2009 (VIEIRA et al., 2010). Em níveis mais elevados, a polinização também apresenta valores expressivos para alguns países. O valor desse serviço ecossistêmico, por exemplo, foi estimado em US$ 119,8 milhões em 2005 para a região do Cabo na África do Sul (ALLSOPP et al., 2008). No Brasil, a polinização contribui em cerca de 30% do valor total da produção do grupo de culturas dependentes de polinizadores e 13% do valor total da produção agrícola brasileira (GIANNINI et al., 2015). Por fim, na escala global, o benefício econômico com a polinização agrícola foi estimado em cerca de 10% do valor total da agricultura (GALLAI et al., 2009; LAUTENBACH et al., 2012). Dessa forma, embora a polinização seja um fenômeno que ocorra na escala local da propriedade rural, esses diversos exemplos demonstram que o seu benefício também repercute em níveis mais elevados, tais como, a economia nacional e global, demandando, assim, metodologias apropriadas para cada nível.

Segundo Hein (2009), o valor dos serviços de polinização não pode ser visto separadamente da produção agrícola, ou seja, um processo que depende de diversos outros insumos, tais como, fertilizantes, pesticidas, trabalho, entre outros. Nesse sentido, a polinização é também um insumo na produção agrícola e, portanto, uma abordagem baseada na função de produção que demonstre a relação entre a quantidade produzida e a combinação de insumos é a mais coerente para a escala local. Alguns exemplos de estudo com essa abordagem são a polinização no café (RICKETTS et al., 2004; OLSCHEWSKI et al., 2006) e na produção de melancia (WINFREE et al., 2011). Esses estudos demonstram que esse método é mais adequado para avaliar a formação da renda do produtor, pois combinando com informações de custo, as estimativas são facilmente adaptadas para calcular o lucro. Outra abordagem ao nível local de análise é o custo de substituição que consiste em estimar o gasto com o manejo de colmeias de abelhas ou com a contratação de trabalhadores para a polinização manual das flores (e.g., maracujá, VIEIRA et al., 2010). No entanto, esse método não representa os benefícios dos polinizadores selvagens em termos de ganho de produtividade e de qualidade na produção agrícola. Portanto, pode não ser útil para traçar estratégias de conservação dos ecossistemas e de seus polinizadores.

Estudos anteriores buscaram sistematizar o processo pelo qual a polinização afeta a produção agrícola e o lucro do produtor, considerando a abordagem da função de produção. Winfree et al. (2011) e Hanley et al., (2014) apresentaram uma aplicação da teoria microeconômica da função de produção ao contexto da polinização agrícola como um insumo de produção. Nesses estudos, a lucratividade do produtor foi estimada pelo valor da produção em função dos serviços de polinização menos os custos de produção. Embora tais estudos reconheçam a existência dos custos associados à gestão dos serviços de polinização (e.g., via reflorestamento ou conservação das áreas de vegetação, manejo de colmeias de abelhas), esses componentes não foram considerados pelos modelos conceituais nem incorporados nas aplicações nos estudos de caso. Além disso, o reflorestamento ou a conservação das áreas de vegetação impõem ao produtor um custo de oportunidade que representa o quanto o produtor está deixando de lucrar por não estar explorando essas áreas com atividades agropecuárias (NAIDOO et al., 2006). Além desses custos, outros processos não foram discutidos, tais como, a interação entre a polinização e os demais insumos agrícolas e o efeito dessa interação na produtividade e a qualidade agrícola. Todos esses componentes precisam ser incorporadas em futuras análises para gerar informações valiosas e aprimorar o processo de tomada de decisão do produtor rural (BREEZE et al., 2016).

No nível de análise da paisagem, o uso de informações geográficas seria de grande utilidade para identificar áreas naturais que possam ser conservadas de modo a preservar os polinizadores e manter os benefícios econômicos na produção agrícola (GIANNINI et al., 2013). Essa abordagem foi usada por estudos anteriores em três principais maneiras: estimando a oferta de polinização mediante o percentual de área de vegetação na paisagem e, assim, assumindo uma oferta constante desse serviço em toda a área agrícola dentro dessa mesma paisagem; usando modelos espaciais de polinização cuja oferta desse serviço varia conforme a distância em relação às áreas de vegetação; e por fim, pela combinação de ambos os modelos (RICKETTS et al., 2004; MORANDIN e WINSTON, 2006; OLSCHEWSKI et al., 2006; CHAPLIN-KRAMER et al., 2011). O uso de informações da paisagem para avaliar o resultado econômico com a conservação auxilia na avaliação da atratividade das políticas ambientais, tendo em vista, a perspectiva do produtor rural.

Partindo do nível da paisagem para outros mais elevados, os primeiros estudos de valoração da polinização no nível nacional ocorreram na década de 1940 (e.g., BUTLER, 1943; METCALF et al., 1962; MARTIN, 1973; LEVIN, 1984). A primeira abordagem foi baseada no valor total da produção de culturas agrícolas dependentes de polinizadores (MELATHOPOULOS, et al., 2015). No entanto, os estudos locais sobre polinização demonstram que o nível de dependência em relação a esse serviço varia amplamente entre os diversos cultivos agrícolas (KLEIN et al., 2007). Por conta disso, outra abordagem foi desenvolvida baseada na taxa de dependência que cada cultura possui em relação aos polinizadores. O nível de dependência das culturas agrícolas em relação aos polinizadores tem sido alvo de diversos estudos (BORNECK e MERLE, 1989; ROBINSON et al. 1989; MORSE e CALDERONE, 2000), sendo o mais recente o artigo de Klein et al. (2007) que tem sido base para diversas avaliações mais recentes. O método da taxa de dependência, também denominado de abordagem bioeconômica por Gallai et al. (2009), tem sido amplamente usado em análises de nível nacional, por exemplo, no México (ASHWORTH et al., 2009), nos EUA (CALDERONE, 2012), na Argentina (CHACOFF et al., 2010), e no Brasil (GIANNINI et al., 2015). Esse método também tem sido usado no nível global (GALLAI et al., 2009; LAUTENBACH et al., 2012). Tais estudos focam no quanto a polinização contribui para o valor total da produção na agricultura, desconsiderando o comércio internacional cuja análise poderia revelar relações de dependências entre os países.

Essas foram as principais abordagens econômicas da polinização agrícola que podem ser aplicadas em diversos níveis para orientar estratégias de conservação da natureza e de proteção aos polinizadores. Os principais desafios em termos de uso sustentável dos polinizadores serão discutidos a seguir, considerando três principais níveis de análise: local, da paisagem, e nacional/global.

3. Desafios para o uso sustentável da polinização em diversos níveis

A proteção dos ecossistemas e do uso sustentável de seus serviços na agricultura depende de como o capital natural é manejado nos sistemas agrícolas. A intensificação agrícola trouxe benefícios em termos de ganho em produtividade, porém com impactos negativos ao meio ambiente por meio do uso intensivo de insumos químicos e de extensas áreas agrícolas. Com isso, uma nova abordagem denominada intensificação ecológica surgiu como uma resposta ao modo tradicional de produção agrícola. Nessa nova abordagem, os serviços ecossistêmicos são manejados nos sistemas agrícolas para elevar os níveis de produtividade agrícola enquanto minimiza os impactos ambientais (BOMMARCO et al., 2013). Assim, a gestão do capital natural faz parte dessa nova forma de equilibrar as demandas produtivas com a conservação dos ecossistemas.

Capital natural é compreendido aqui como um ecossistema que fornece um fluxo de serviços ao longo do tempo (COSTANZA et al., 2017). Com o avanço na problematização ambiental, o manejo do capital natural baseou-se em duas concepções associadas ao seu grau de substituição por outras formas de capitais. Essas duas concepções foram denominadas de sustentabilidade fraca e sustentabilidade forte (PEARCE, 2006). A primeira, baseada na economia neoclássica, argumenta que, mesmo havendo ameaças ao capital natural (e.g., declínio de populações de polinizadores ou destruição de habitat naturais) as necessidades humanas (e.g., consumo de alimentos e produção agrícola) poderão ser satisfeitas com o avanço tecnológico, pois ele permitirá a substituição parcial do capital natural por outras formas de capitais (e.g., implantação de colmeias de abelhas ou, então, a contratação de pessoas para a polinização manual) (PEARCE, 2006). Por outro lado, a sustentabilidade forte, baseada na economia ecológica, argumenta que, mesmo havendo a possibilidade de substituição, ela ocorreria somente de forma parcial, pois a relação entre os capitais é primordialmente de complementariedade (EKINS et al., 2003). Isso ocorre pelos atributos da absoluta essencialidade (associado ao valor de existência) e da irreversibilidade dos impactos ambientais que são inerentes aos ecossistemas.

A gestão dos serviços de polinização na agricultura se divide em três principais formas de manejo, considerando a relação entre o capital natural e outras formas de capitais. O primeiro deles está relacionado à conservação ou restauração de áreas de vegetação nativa, inclusive, pequenas áreas na borda dos campos agrícolas, aumentando a heterogeneidade da paisagem (GARIBALDI et al., 2014; PYWELL et al., 2015). O segundo se refere ao manejo menos intensivo na agricultura em termos do uso de insumos químicos (i.e., fertilizantes e pesticidas) (HENRY et al., 2012; RAMOS et al., 2018). Essas duas primeiras formas de manejo da polinização estão relacionadas à intensificação ecológica. Por fim, a terceira forma de manejo dos serviços de polinização envolve o uso de colmeias de abelhas (um capital feito pelo homem) (CUNNINGHAM e FEUVRE, 2013) para suplementar os serviços de polinização em campos agrícolas que apresentam elevado déficit de polinização (GARIBALDI et al., 2013) ou, então, quando determinadas culturas necessitam de polinizadores especializados, por exemplo, o caso do maracujá que é polinizado por abelhas grandes conhecidas como mamangavas (FREITAS e OLIVEIRA FILHO, 2003). Essas estratégias de manejo de polinizadores ocorrem, principalmente, em dois níveis espaciais: o local e o da paisagem.

Os produtores rurais tem um papel chave no nível local, pois são eles que adotam essas três principais formas de manejo. No entanto, uma das grandes dificuldades para o produtor é conhecer a viabilidade econômica de tais alternativas. Nesse sentido, estudos de viabilidade econômica que consideram o ganho econômico decorrente dos serviços de polinização são importantes para demonstrar a atratividade dos projetos de restauração de áreas naturais. Além disso, um dos grandes empecilhos é o custo de oportunidade associado às áreas de conservação da natureza, pois tais espaços representam limitações à expansão dos campos agrícola e, por fim, também ao lucro do produtor (KAMAL et al., 2015). Por fim, a criação de modelos que sistematizem a avaliação econômica, considerando tais componentes de manejo de polinizadores (incluindo seus custos), contribuirá para o planejamento agrícola desses produtores.

No nível da paisagem, a conservação/restauração da natureza é fundamental, especialmente daquelas áreas localizadas dentro das terras agrícolas pertencentes aos agentes privados, pois elas abrigam grande parte da biodiversidade (SOARES-FILHO et al., 2014). Contudo, proteger tais áreas é um desafio porque os custos são individualizados enquanto os benefícios são coletivos (LIU et al., 2008; EHRLICH et al., 2012). A conservação em terras privadas gera externalidades positivas em termos de serviços de polinização para os produtores vizinhos. Além disso, diversos outros serviços ecossistêmicos são gerados, beneficiando a sociedade como um todo (e.g., sequestro de carbono, proteção aos recursos hídricos, entre outros). As externalidades positivas, nesse caso, se referem aos benefícios gerados fora do sistema de produção agrícola e que, portanto, não são apropriados pelo produtor que pratica as ações de conservação/restauração da vegetação. Portanto, os agentes que desenvolvem e estabelecem as políticas ambientais são essenciais na criação de mecanismos de internalização de tais benefícios, pois estes tem o potencial de motivar os produtores a adotarem as ações de proteção aos polinizadores.

Conforme o princípio da adicionalidade, os benefícios econômicos decorrentes de políticas ambientais seriam concedidos somente àqueles que ultrapassassem os níveis de conservação de áreas naturais que fossem estabelecidos pelas leis ambientais (ENGEL et al., 2008). Por exemplo, o Código Florestal Brasileiro determina que as propriedades rurais localizadas no cerrado devam conservar no mínimo 20% de vegetação nativa. Assim, aqueles que conservam acima desse percentual poderiam receber uma compensação econômica devido à restrição aos seus campos agrícolas pelas áreas conservadas adicionais. Nesse sentido, tais compensações poderiam também incluir a internalização das externalidades positivas, por assim, as políticas ambientais poderiam equilibrar as demandas por conservação com a viabilidade econômica dos sistemas agrícolas.

Em níveis de análise mais elevados (i.e., nacional e global), um dos grandes desafios do século XXI é regular a produção nacional para diminuir os impactos ao meio ambiente. Tanto a produção agrícola quanto o comércio internacional cresceram nas últimas décadas, mas foi somente durante a criação da Organização Mundial do Comércio (OMC) em 1995 que a proteção do meio ambiente foi considerada como parte importante para a sustentabilidade do comércio internacional (ALMEIDA et al., 2010). No entanto, a economia de grande parte dos países mais pobres está baseada na produção e exportação de commodities agrícolas. Considerando que os países desenvolvidos enriqueceram explorando o capital natural dos atuais países em desenvolvimento, esses últimos demandam o seu direito ao desenvolvimento e sua soberania nacional para explorarem suas riquezas com maior liberdade (ALMEIDA et al., 2010). No entanto, seguir a mesma trajetória de desenvolvimento baseado no uso insustentável dos recursos naturais e dos serviços ecossistêmicos não faz mais sentido no atual contexto em que existem diversas alternativas para conciliar as demandas produtivas com a conservação da natureza. Essa trajetória baseada no uso sustentável da natureza fundamentou a necessidade dos países mais desenvolvidos auxiliarem os países em desenvolvimento, por exemplo, por meio de transferência de recursos financeiros e tecnologias. Assim, a coordenação ambiental entre os países é fundamental para o desenvolvimento sustentável global.

O crescimento populacional impulsionou a produção de produtos dependentes de polinizadores ao redor do mundo, com efeitos também sobre o crescimento da área agrícola dedicada a esses produtos, principalmente nos países em desenvolvimento (AIZEN et al., 2008 e 2009a). A agricultura está condicionada às condições ambientais (e.g., oferta de polinizadores pela biodiversidade), porém o consumo é dependente dos padrões de renda e de poder aquisitivo. Esses fatores provocam um deslocamento geográfico entre a esfera produtiva e de consumo via comércio internacional, que tem acelerado a produção nos países exportadores com efeito danoso ao meio ambiente (MAYER et al., 2005; LENZEN et al., 2012). O impacto do comércio internacional no meio ambiente tem sido amplamente avaliado, por exemplo, com as emissões de gases do efeito estufa, exportações de resíduos sólidos e no uso da água e da terra, mas os impactos em relação aos polinizadores permanecem ainda não esclarecidos.

Uma das formas de quantificar os recursos naturais que usados na produção de commodities para a exportação é por meio do conceito de “recurso virtual” (e.g., água virtual HOEKSTRA e HUNG, 2002; e terra virtual, REES, 1992). Esse conceito representa a quantidade do recurso usado durante o processo de produção e que foi virtualmente comercializado. Os fluxos da água e da terra virtuais já foram amplamente estudados, porém os fluxos virtuais dos serviços de polinização ainda não foram explorados. O entendimento desse fluxo contribuirá para uma possível coordenação internacional para estimular a adoção de práticas amigáveis aos polinizadores nos sistemas agrícolas de exportação (e.g., via ajuste de preços internacionais, transferência de recursos ou tecnologia de baixo impacto aos polinizadores). Tais ações serão relevantes principalmente em países em desenvolvimento com baixa capacidade de adotar estratégias de proteção à biodiversidade, pois o esgotamento dos seus ecossistemas pode comprometer tanto a renda gerada via exportação quanto a sua própria segurança alimentar.

4. Problema e estrutura da tese

Considerando os pontos acima mencionados, o questionamento central desta pesquisa é: compreender, em diversos níveis, quais são os benefícios socioeconômicos associados aos serviços de polinização agrícola. Para responder a essa pergunta, o tema será abordado em três níveis espaciais de análise (i.e., local, da paisagem, nacional/global) avaliando determinados impactos socioeconômicos decorrentes do declínio de polinizadores por meio de estudos de caso associados aos diferentes agentes tomadores de decisões (Fig. 1). Assim, espera-se que os resultados sejam úteis para a sustentabilidade do planejamento agrícola e futuras políticas públicas de proteção aos polinizadores, de modo a conciliar as demandas produtivas com a responsabilidade ambiental de conservação da natureza.

FIG. 1 – Mapa da tese com as perguntas específicas associadas a cada nível de análise.

A tese está estruturada em três capítulos (um para cada nível de análise), além da introdução e da conclusão/síntese.

O primeiro capítulo, *Economic framework for valuating ecosystem service management at farm scale - a tool for ecological intensification*, será focado na escala local e buscará responder como o manejo dos serviços de polinização, em interação com o manejo convencional agrícola, afeta o resultado econômico do produtor. Para orientar esta análise, o estudo irá adaptar o modelo tradicional microeconômico da função de produção considerando os serviços de polinização como um insumo proveniente do capital natural e do manejo de colmeias de abelhas. Além disso, irá considerar um convencional insumo agrícola para analisar a sua interação com o manejo de polinizadores. Esse modelo de produção irá compreender tanto os aspectos da produtividade quanto da qualidade dos produtos agrícolas. Ele também irá incorporar os custos associados ao manejo de polinizadores e ao manejo convencional. O manejo de polinizadores selvagens se dará por meio da gestão do capital natural, ou seja, considerando o custo de oportunidade das áreas de conservação e a viabilidade econômica da restauração da vegetação nativa. Já o manejo das colmeias de abelhas se dará pelo seu custo de implantação nos campos agrícolas. Os resultados irão ajudar a preencher a lacuna de informação sobre o custo e benefício do manejo de polinizadores ao nível da propriedade rural e, assim, servir de base para os produtores planejarem o seu manejo considerando a polinização como um importante insumo agrícola.

O segundo capítulo, *Nature conservation policies may increase farmers' profitability via pollination services*, irá tratar da escala da paisagem e avaliará como as atuais políticas de conservação da natureza podem beneficiar economicamente o produtor por meio dos serviços de polinização. Neste estudo, o intuito é verificar se os serviços de polinização viabilizam a produção mesmo com as áreas protegidas restringindo os campos agrícolas. Além disso, o estudo também considerará a inclusão de mecanismos de internalização das externalidades decorrentes da conservação de áreas acima do exigido pela legislação ambiental. Este estudo será importante para a compreensão dos impactos econômicos decorrentes dos instrumentos legais de conservação da natureza e seus efeitos na polinização agrícola.

Para responder aos questionamentos específicos referentes ao primeiro e ao segundo capítulo, foram coletadas informações sobre polinização agrícola em campos cultivados com o feijão comum (*Phaseolus vulgaris L.*). Recentemente foi publicado o primeiro "Relatório Temático sobre Polinização, Polinizadores e Produção de Alimentos no Brasil" que destacou que 76% das plantas utilizadas para produzir alimentos no Brasil são dependentes de polinizadores cuja contribuição equivale a R$ 43 bilhões em 2018, estando cerca de 80% desse valor concentrado em quatro cultivos (i.e., soja, café, laranja e maçã) (WOLOWSKI et al., 2019). O feijão é uma cultura amplamente consumida no Brasil e, por isso, é relevante tanto para a segurança alimentar quanto para a economia agrícola do país (MELO et al., 2009; SOUZA e WANDER, 2014; IBGE, 2018). Esta cultura possivelmente não consta entre os quatro principais cultivos devido a estudos anteriores considerarem que a polinização contribui apenas com 5% do seu valor de produção (KLEIN et al., 2007). No entanto, estudos recentes demonstraram que a produção nessa cultura pode ser aumentada em até 35% com os serviços de polinização (IBARRA-PERES et al., 1999; KASINA et al., 2009a e 2009b; RAMOS et al., 2018). Portanto, a escolha do feijão como estudo de caso permitirá destacar a importância da polinização para a agricultura brasileira.

Os campos de feijão estudados estiveram localizados no Distrito Federal e em Goiás (o cerrado brasileiro). No Brasil, aproximadamente 53% da vegetação nativa brasileira está em propriedades privadas (SOARES-FILHO et al., 2014), sendo que, no cerrado, cerca de 40% da área de vegetação localizadas em propriedades rurais ainda pode ser legalmente desmatada (STRASSBURG et al., 2017). Logo, a região de estudo é importante porque a sua biodiversidade está sendo ameaçada pela expansão de sistemas agrícolas baseados em monoculturas e intenso uso de insumos químicos (STRASSBURG et al., 2017). Especificamente para o segundo capítulo, o estudo terá como arranjo institucional o Código Florestal, pois é a lei que define as áreas protegias dentro de propriedades privadas no Brasil. Por fim, considerando que nessa região o feijão é amplamente produzido em monoculturas com o uso intensivo de insumos químicos, que prejudicam os polinizadores, os dois capítulos fornecerão informações para auxiliar na definição de estratégias de proteção aos polinizadores.

O terceiro capítulo, *International trade of pollinated-dependent crops is increasing cropland in less developed countries*, focará na escala nacional/global para avaliar como a crescente demanda global por produtos dependentes de polinizadores está pressionando os ecossistemas. Com isso, este estudo buscará demonstrar como o comércio internacional dos produtos dependentes de polinização está associado à expansão das terras agrícolas nos países exportadores. Este estudo também irá demonstrar a dependência mútua entre os países sobre os seus serviços de polinização através do fluxo virtual de polinizadores. Para isso, será usado o método de taxas de dependência de polinizadores das culturas agrícolas (KLEIN et al., 2007; GALLAI et al., 2009) e dados da Organização das Nações Unidas para a Agricultura e Alimentação (FAO-UN, 2018) de comércio, produção e área agrícola de 52 culturas dependentes de polinizadores para 115 países. Por último, busca-se aqui compreender a associação entre os impactos ambientais e o comércio internacional de produtos agrícolas dependentes de polinizadores e verificar se essa relação é afetada pelo nível de desenvolvimento dos países. Nesse sentido, políticas internacionais de conservação dos polinizadores serão discutidas em função do seu potencial em tornar o comércio internacional mais sustentável.

CAPÍTULO 1 - Economic framework for valuating pollinator management at farm level: a tool for ecological intensification[1][2]

Abstract

Although, pollination services may increase crop yield and quality of many crops worldwide, economic benefits provided by this ecosystem service are rarely taken into consideration in the farmers' decision-making process. Farmers' profitability depends on a complex set of management choices and product characteristics, so assessing pollination services as an agricultural input is essential. Here, we proposed a conceptual framework that links pollinator management (i.e., natural capital and honeybee managements) and more conventional practices (e.g., fertilizers) to estimate the economic output based on crop yield and product quality. We tested this framework on the common bean (*Phaseolus vulgaris*), an economically important crop and a worldwide food staple that greatly benefits from pollinators. Common bean yield and quality was improved by wild pollinators, and this effect on profit was maximized under a scenario of intermediate fertilizer input. Opportunity cost was below farmers' profit in a farmland area (78 ha) with vegetation cover of 35 up to 75%. Economic feasibility of reforestation was feasible using natural regeneration and direct seeding technics, being compensated in less than 10 years. In addition, using plantation of seedling technic, reforestation was feasible for farmland that already has at least 20% of vegetation cover. Thus, economic feasibility of natural capital management can enhance farmers' profit via ecosystem services, depending on how such capital is managed. Framed within the ecological intensification approach, the economic benefit detected with the proposed framework can incentive behavioral changes among farmers toward pollinator-friendly management, e.g., by reducing chemical inputs or reforestation. In addition, market instruments, such as product certification or payment for environmental services, might improve the attractiveness of pollinator-friendly practices.

Key-words: Cropland management; ecological intensification; common bean.

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1. Introduction

Natural capital consist of all natural resources available that provides a number of ecosystem services that benefit agriculture, crop production and human wellbeing (COSTANZA et al., 1997, 2017; MEA, 2005). Yet globally, as the vast majority of natural vegetation is not legally protected (WATSON et al., 2014), such services are declining (MEA, 2005; GARIBALDI et al., 2011b). Farmers often have areas of natural vegetation on their properties; in Brazil, for example, 53% of native vegetation is on privately owned land (SOARES-FILHO et al., 2014). Conventional cropland management planning typically ignores the freely acquired benefits from ecosystem services (e.g., crop pollination), and only takes into consideration purchased inputs, such as chemical fertilizer and pesticides (SIMPSON, 2014). Quantifying the economic benefits of ecosystem services is an essential step towards integrating these services into land management plans and incentivizing the implementation of sustainable farming practices (BALMFORD et al., 2002; NAIDOO et al., 2006; TEEB, 2010).

One example of those ecosystem services is crop pollination that benefits a large number of agricultural products via wild and managed pollinators (KLEIN et al., 2007; GARIBALDI et al., 2013 and 2016a). Pollination is the transfer of pollen between plats that contributes to enhance yield and improve crop quality via genetic information exchange, including their nutritional traits (BRITTAIN et al., 2014) and aesthetic aspects (GARRATT et al., 2014; KLATT et al., 2014) (see Table 1). For example, apple and strawberry grade is based on shape and size, which may be improved by pollination services (GARRATT et al., 2014; KLATT et al., 2014). Although, this service is important for farmers and consumers, pollinators are under threats due to agricultural intensification, especially, via extensive cropland areas and associated destruction of natural habitats, and chemical input application (POTTS et al., 2010 and 2016). Thus, preserving pollinators and their sustainable use is crucial to maintain the benefits received by community.

Pollination services can be managed via three main practices: landscape management of natural capital; field-level practices; and bee hives management. The first is associated to landscape management of fragments of natural habitat that provide a flow of services over time (COSTANZA et al., 2017). Pollinator-friendly landscape management may involve expenditures to reforest, and/or conserving already existent natural areas that may provide enhanced profit via pollination services (GARIBALDI et al., 2014). Both conservation and restoration of vegetation areas also involve opportunity costs related to restricting cropland area for natural areas maintenance (NAIDOO et al., 2006). The second, field-level practices also contribute to enhance pollination service supply, for instance, via changes in weed control and chemical input management (GARIBALDI et al., 2014). More specifically, local pollinator-friendly practices encompass the reduction of chemical input, such as inorganic fertilizers and pesticides (HENRY et al., 2012; RAMOS et al., 2018), and adding alternative flower resources in the margins or within crop fields (BLAUW and ISAACS, 2014; CARVALHEIRO et al., 2011). Finally, other frequently-used practice is the introduction of supplemental pollinators via bee hives management (e.g. *Apis mellifera* and *Bombus terrestris*) (CUNNINGHAM and FEUVRE, 2013; VELTHUIS and DOORN, 2006), although this is unsuitable for some crop systems (GARIBALDI et al, 2013). However, when aiming to improve profit, farmers frequently adopt practices that ultimately reduce the economic benefits associated to ecosystem services, such as the conversion of natural habitats into cropland or intensification of chemical inputs (e.g., inorganic fertilizer) (POLASKY et al., 2011; GOLDSTEIN et al., 2012).

The Millennium Ecosystem Assessment (MEA, 2005) stimulated the development of several conceptual frameworks to assess ecosystem and their services (BOEREMA et al., 2017). A conceptual framework for crop pollination was proposed to associate land-use change to pollination services on crop field, leading to economic value (KREMEN et al., 2007). An economic framework for pollination services at farm-level was proposed by Winfree et al (2011). Such framework associated this service with enhanced yield and pollinator management cost (e.g., bee hive application) in order to estimate farmers' profit, which is highly relevant for farmer's decision-making process (BREEZE et al., 2016). Another economic framework was proposed by Hanley et al. (2014) considering the economic output as a function of pollination service and other inputs, but with not considering potential interactions between them. However, both economic frameworks neglected the effect on crop quality, which is important to consider market price variations (see

KAWASAKI and UCHIDA, 2016).

The complexity in pollinator management cost was also not appropriately included in previous economic frameworks. Pollinator management may involve high expenditure in vegetation restoration in initial period that could be compensated by enhanced profit in the next periods. For example, BLAAUW and ISAACS (2014) found that the cost to reforest 0.8 ha around of 4 ha of a blueberry field to enhance pollination services would be compensated in 4 years by enhanced profit. In addition, another component is the opportunity cost of restoration and/or conservation of vegetation areas is important for management decision. OLSCHEWSKI et al (2010) provided a comprehensive study on trade-off between timber production, carbon sequestration and pollination services on coffee fields, and found that pollination services compensates the economic loss due to limited timber extraction. Thus, an economic framework is still needed to integrate economic feasibility and opportunity cost to guide future management plans that aims conciliate economic benefits with pollinator protection.

Here, we aim to understand how pollination management interacts with conventional cropland management and affect farmers' economic output. To answer this question, we present and test a conceptual economic framework to better support decision-making processes for management and conservation. We used a traditional approach that is based on microeconomic theory of production function to propose an economic framework taking into account the interaction between pollinator management and conventional management practices, and estimates of profit by accounting for yield and crop quality aspects, costs and revenue. Based on estimated profit, we assessed the opportunity cost and economic feasibility of restoration/conservation of vegetation areas.

We focus on common bean (*Phaseolus vulgaris*), an important crop for food security and economy, particularly in South America where about 17% of the world's beans are consumed (FAO, 2018). In Brazil, this crop represents nearly 12% of the total value of all annual crops produced nationally (SOUZA and WANDER, 2014; IBGE, 2018). In addition, this important food staple is typically produced under conventional management practices and benefits from pollination services (KASINA et al., 2009a and 2009b; RAMOS et al., 2018). Even though the common bean flower can be self-pollinated, previous studies found that, depending on variety, pollinators may enhance crop yield (weight of seed in pods) (IBARRA-PEREZ et al., 1999) and protein content (see Table 1; KASINA et al., 2009a and 2009b). Previously, we found that common bean benefits from pollination services in terms of yield (i.e., weight per pod) when the level of fertilizer application was intermediate or low (i.e., < 72 kg/ha of nitrogen) (see Annex A - RAMOS et al., 2018). This result corroborates with others studies (see BRITTAIN et al., 2014; MARINI et al., 2015; TAMBURINI et al., 2017) and indicates that pollination benefits may be maximized at less intensive crop systems, supporting the ecological intensification approach.

Our approach intends to assess the economic feasibility of the most appropriate pollinator management strategy for common bean production. Although recognizably a utilitarian approach, this will be a useful addition to the farmland management toolbox to help better understanding the influence of pollinators on financial profit of common bean and how pollination services management can be integrated into cropland management plans. Finally, this assessment will be useful to inform farmers on how to deal with the trade-off associated to land-use for crop production and for pollination services provision.

Box 1 – Valuation of crop pollination at local level

The core of crop pollination valuation is how this ecosystem service benefits human society by improving crop quality and yield and how human well-being could be affected by the absence of such service. Pollinator decline has different effects at local and large level (HEIN, 2009). Depending on the pollinator-dependence of the crop, pollinator declining at local level has a great potential to affect farmers profit by reducing quantity and quality of their production. However, such local impact has little effect on the overall supply of crop and market price, especially at both national and international market (KEVAN and PHILLIPS, 2001).

Several valuation approaches at local level focused on how pollination services support farmers' income. Pollination declining could affect agricultural production by reducing yield and crop quality, or increasing production cost, so valuation approach generally focused on the variation of farmers' benefits by estimating variation of production value or production cost (WINFREE et al., 2011). Previous studies aimed to review valuation methods (see MBURU et al., 2006; HEIN, 2009; BAUER, 2014; MELATHOPOULOS et al., 2015; BREEZE et al., 2016), and, here, we present the main approaches used at local scale.

Production value approach: Crop pollination is frequently seeing as another agricultural input, so this method is based on the physical effects of pollination supply on agricultural production and value. This approach is based on the production function that can be estimated using data gathered in research field. Some critics point out that the method frequently ignores the effect of other inputs (and their cost), that it overestimates pollinator value, that market price will not increase with reduction in crop supply, and, that it does not recognize alternatives for cropland management to deal with pollination declines (BAUER, 2014).

Production cost: the assumption here is, in a scenario of pollinator absence, how much the cost would increase for farmers implement some strategy to provide the same level of pollination service (ALLSOPP et al., 2008). Some alternatives do exist to deal with pollination deficit at local scale that could be purchased at market. For example, in Brazil, the replacement cost in passion fruit was assessed in 4.677,08 USD/ha over 2007-2009 taking into consideration the hand pollination management, in which the cost was represented as the minimal national wage per employee (VIEIRA et al., 2010). Another example is the replacement cost of native pollinators in watermelon production in New Jersey and Pennsylvania, USA, which was estimated in \$0.21 million year^{-1} in 2005 (WINFREE et al., 2011). This method neglects the benefit received by farmers from native pollinators because it is tied to bee hives and labor prices (BREEZE et al., 2016).

These two approaches can be integrated to estimate farmers' profit (i.e., the net value between production, or revenue, and cost). **Profit estimation** approach combines production value and cost of all agricultural inputs (including pollination services) in order to estimate farmers' benefits in terms of profit. This method is useful to understand how pollination services can be integrated into cropland management in order to define strategies for pollinator management (WINFREE et al., 2011). Although previous studies that used this approach recognized the cost of native pollinators management do exist (GARRATT et al., 2014), few attention was given to the economic feasibility associated to restoration/conservation of natural vegetation (see, BLAAUW and ISAACS, 2014) and on opportunity cost related to such set-aside areas (see OLSCHEWSKI et al., 2010). Both economic feasibility and opportunity cost assessments are essentials to improve farmers' decision-making process.

Table 1 – Review of qualitative aspects of crops that are influenced by pollinators. '*' indicates a qualitative characteristic that is important for defining the crop grade used on market.

Crop	Nutritional traits (biochemical elements)	Aesthetic aspects	Region	Source
Almond (*Prunus persica*)	Fat and vitamin	None	USA	BRITTAIN et al., 2014
Apple (*Malus domestica*)	Sugar concentration and mineral content	Size (width)*, firmness, shape* (deformation)	UK	GARRATT et al., 2014
	None	Size* (width) and shape* (deformation)	UK	GARRATT et al., 2016
	None	Size* (diameter) and shape*	South Africa	MOUTON, 2011
Buckwheat (*Fagopyrum esculentum*)	None	% of filled seeds	Poland	BARTOMEUS et al., 2014
Coffee (*Coffea arabica*)	None	% of peaberries	Costa Rica	RICKETTS et al., 2004
	None	% of peaberries	Colombia	BRAVO-MONROY et al., 2015
Bean (*Vicia faba*)	Nitrogen content	None	UK	BARTOMEUS et al., 2014
Mistletoe (*Viscum album*)	None	Presence of berries*	UK	OLLERTON et al., 2016
Holly (*Ilex aquifolium*)	None	Presence of berries*	UK	OLLERTON et al., 2016
Jatropha (*Jatropha curcas*)	Oil quality	None	South Africa	NEGUSSIE et al., 2015
Oilseed rape (*Brassica napus*)	Oil* and chlorophyll* content	None	Sweden	BOMMARCO et al., 2012
	Oil content	None	Sweden	BARTOMEUS et al., 2014
Strawberry (*Fragaria x ananassa*)	Sugar content	Shape* (deformation), color*, size* (diameter), firmness, and shell life.	European Union	KLATT et al.,2014
	None	Color and shape	Germany	BARTOMEUS et al., 2014
Bean (*Phaseolus vulgaris*)	Protein content	None	Kenya	KASINA et al., 2009a and 2009b
Cowpea (*Vigna unguiculata*)	Protein content	None	Kenya	KASINA et al., 2009a and 2009b
Tomatoes (*Solanum esculentum*)	None	Size (diameter)	Kenya	KASINA et al., 2009a and 2009b
Capsicum (*Capsicum annum*)	None	Size (diameter)	Kenya	KASINA et al., 2009a and 2009b
Passion fruit (*Passiflora edulis*)	None	Size (diameter)	Kenya	KASINA et al., 2009a and 2009b
Sunflower (*Helianthus annuus L.*)	Oil content	None	Kenya	KASINA et al., 2009a and 2009b

Source: Elaborated by authors.

2. Economic framework for crop pollination

To assess the economic benefit of crop pollination, we propose a framework based on an input-production-output approach in order to simulate the agricultural production process (DEBERTIN, 2012). Here we will apply a traditional model used in microeconomics analysis in a new context of pollination services as an agricultural input. The step-by-step economic framework for assessing crop pollinators (Fig. 2) takes into account two basic strategies for pollinator management: i) practices that maximize the benefits of natural capital and ii) the use of managed pollinators, a human-made capital. Management measures not aimed at pollinators were grouped together as a single input to simplify graphical representation. Depending on the amount of information available, however, these management practices may be separated into multiple components (e.g. pesticide application, fertilizer application, tillage, etc.). Although pollination is the focus of this study, the framework could similarly be expanded to include other ecosystem services. Below, the steps of the framework are described in detail.

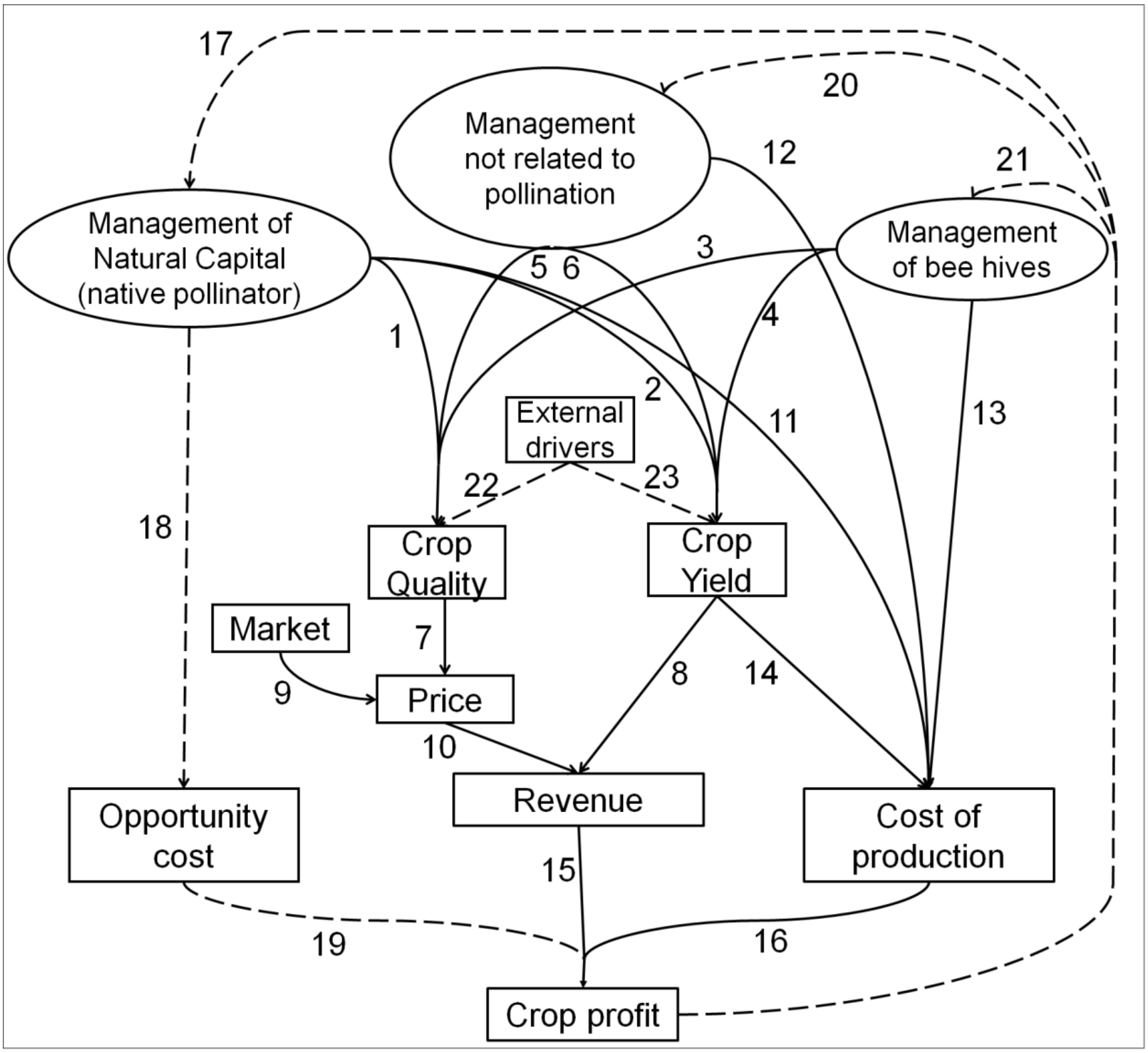

FIG. 2 – Conceptual framework for economic assessment of crop pollination at the farm scale. Dashed lines indicate potential feedback effects that could influence further management strategies.

Source: Elaborated by authors.

2.1. Effect of management practices on yield and crop quality

As described above, crop pollination input can be directly enhanced by management practices related to natural capital (e.g. improvement of nesting sites and floral resources) or be supplemented with managed bee hives (Fig. 2). This last represents a human-made capital that aims to meet pollinated-crop demand by offsetting the pollination deficit due to insufficient services from natural capital (VIANA et al., 2014). Those management practices directly affect crop production. For example, flower visitation by wild and managed pollinators may promote cross-pollination, which enhances the yield and quality of several crops (arrows 1, 2, 3, and 4 – Fig. 2) (KLEIN et al., 2007; GARRATT et al., 2014; GARIBALDI et al., 2016a). Crop production is also influenced by conventional agricultural management, which involves the allocation of agricultural inputs (Fig. 2) (DEBERTIN, 2012). Management not related to pollination also influences crop yield and quality, for example, by regulating nutrient supply or controlling pests (arrows 5 and 6 – Fig. 2).

The interactions between different types of management practices that indirectly influence crop production are also considered in the framework (indicated by union of the arrows 1, 3 and 5 for quality, and 2, 4, and 6 for yield). As an example of such interactive effects, wild pollinator populations can increase the effectiveness of managed bees, affecting the provision of natural pollination services (GREENLEAF and KREMEN, 2006; DOHZONO and YOKOYAMA, 2010; CARVALHEIRO et al., 2011). Also, pesticide application has well known lethal and non-lethal effects on pollinators (HENRY et al., 2012; FRAZIER et al., 2015), while fertilizers can alter flower resource availability and quality, influencing the pollinator visitation rates and overall behavior (HOOVER et al., 2014; CEULEMANS et al., 2017; RAMOS et al., 2018).

2.2. Effects of management practices on crop profit

Crop quality defines market price of crops (arrows 7 and 9 – Fig. 9) and management practices affect the proportion of crop yield that fall into each crop quality class (arrow 8 - Fig. 2). Revenue is then estimated by multiplying the proportion of yield in each quality class by their respective quality-adjusted price (arrows 8 and 10 – Fig. 2). Although crop quality may be graded by both nutritional traits and aesthetic aspects (see Table 1), many crops are graded only by the latter (KAWASAKI and UCHIDA, 2016). In the case of common bean, seed size and color are two important aspects for the definition of market price (farmers' personal communication; BRASIL, 2008 and 2009) (see the study application for more detail). Another example, while the sugar content and firmness of apples are valued by consumers, apple crop grades are defined by a combination of size and shape in the UK market (GARRATT et al., 2014).

Production costs encompass expenditure related to natural capital management (e.g., plantation of flower stripes, restoration of vegetation areas, arrow 11 – Fig. 2, see NAIDOO et al., 2006; BLAAUW and ISAACS, 2014), and bee hive management (e.g., rental costs, arrow 13 – Fig. 2, see CUNNINGHAM and FEUVRE, 2013). Agricultural management costs that are not related to pollinators include expenditure with fixed inputs (arrow 12 – Fig. 2) and variable inputs that are related to yield (arrow 14 – Fig. 2) (see DEBERTIN, 2012). Finally, farmers' profit is defined as the difference between revenue and production costs (arrows 15 and 16 – Fig. 2).

2.3. Potential feedback effects, opportunity costs, and external drivers

Increased profit from pollinator management practices may result in feedback effects through changes in future farmers' behavior. For example, management decisions that favor pollinator-friendly management could bring about new investments in natural capital (arrow 17 – Fig. 2), which are associated with extra management costs (arrow 11 – Fig. 2) as well as opportunity costs (i.e., potential economic gain due to profitable direct use of the area under natural vegetation) (arrow 18 – Fig. 2) that affect the attractiveness of the restoration (arrow 19 – Fig. 2) (NAIDOO et al., 2006; ADAMS et al., 2010). Opportunity costs may be related to loss of opportunity to expand cropland or livestock activities (OLSCHEWSKI et al., 2006). The inclusion of opportunity costs in this framework allows direct comparison of different future management strategies, which is crucial for supporting farmers' decision-making process.

Other potential feedbacks include modifying conventional farming practices to make them more sustainable (e.g., reduction in chemical input and crop land area, or adoption of diversified crop systems) (arrow 20 – Fig. 2) or a shifting to alternative crops with lower or no dependence on pollinators for production (HEIN, 2009). For certain crops, such as pumpkin, coffee, passion fruit, grapefruit, mango, and others (GARIBALDI et al., 2013), farmers may also be motivated to install bee hives to supplement the pollinating services already provided by natural capital (arrow 21 – Fig. 2) instead of restore vegetation areas. However, changes in farmers' behavior are often uncertain and difficult to predict due to several factors, being mostly controlled by others stakeholders at another level of analysis (e.g., environmental policy enforcement, consumer and market response, farmer competition, morality, availability of technology, education, the role of institutions, community organization, farm size, among others) (SNOO et al., 2013; BRAVO-MONROY et al., 2015). In addition, environmental conditions associated to biotic and abiotic factors, such as water scarcity, climate change, pest, also affect farmers' decision-making process. All those factors were grouped as an external driver component (Arrows 22 and 23 – Fig. 2) (ROCHA et al., 2019). Those external drivers affect further strategies of cropland management of farmers, for example, period of water scarcity stimulates the adoption of irrigation or the appearance of pest interfere in pesticide application. To highlight all those uncertainty, we used dashed lines for arrows 17 up to 23 (Fig. 2).

3. Testing the framework on common bean pollination

3.1. Study system

We used the framework to understand the effects of crop pollination on yield and crop quality of common bean and whether farmers' profitability is affected by pollinator management strategies. We also assessed the opportunity cost and economic feasibility to implement those strategies. Common bean plantations were located in the states of Distrito Federal and Goiás (Brazil) (Figure 3). Farmers were contacted via the Farming Cooperative of Region of Distrito Federal (COOPA/DF, abbreviation in Portuguese). All properties are owned by large scale farmers (average of 113 ha, ranging from 35 to 236 ha) and apply a conventional cropland management, involving similar levels of pesticide application.

The study area is embedded in the “Cerrado” biome, which is a biodiversity hotspot (MYERS et al., 2000) that is under threat by agribusiness expansion (STRASSBURG et al., 2017). The common bean was selected because it benefits from pollination service in terms of yield (IBARRA-PERES et al., 1999; RAMOS et al., 2018) and quality aspects (e.g., protein content, KASINA et al., 2009a and 2009b). Here, we explored if pollinators also contribute to valuable aesthetical aspects of common bean that are important for economic assessment (i.e., seed size and color) (see below). Moreover, this crop is produced at both large and small scales. Large scale production in our study region involves intensive monocultures with high chemical inputs (e.g. fertilizers and pesticides). Our research focused on the cultivar “BRS Estilo” (commercially known as “carioca”), which was developed by the Brazilian Agricultural Research Corporation (*Empresa Brasileira de Pesquisa Agropecuária* – Embrapa, in Portuguese) and is currently largely produced and consumed in Brazil (MELO et al., 2009).

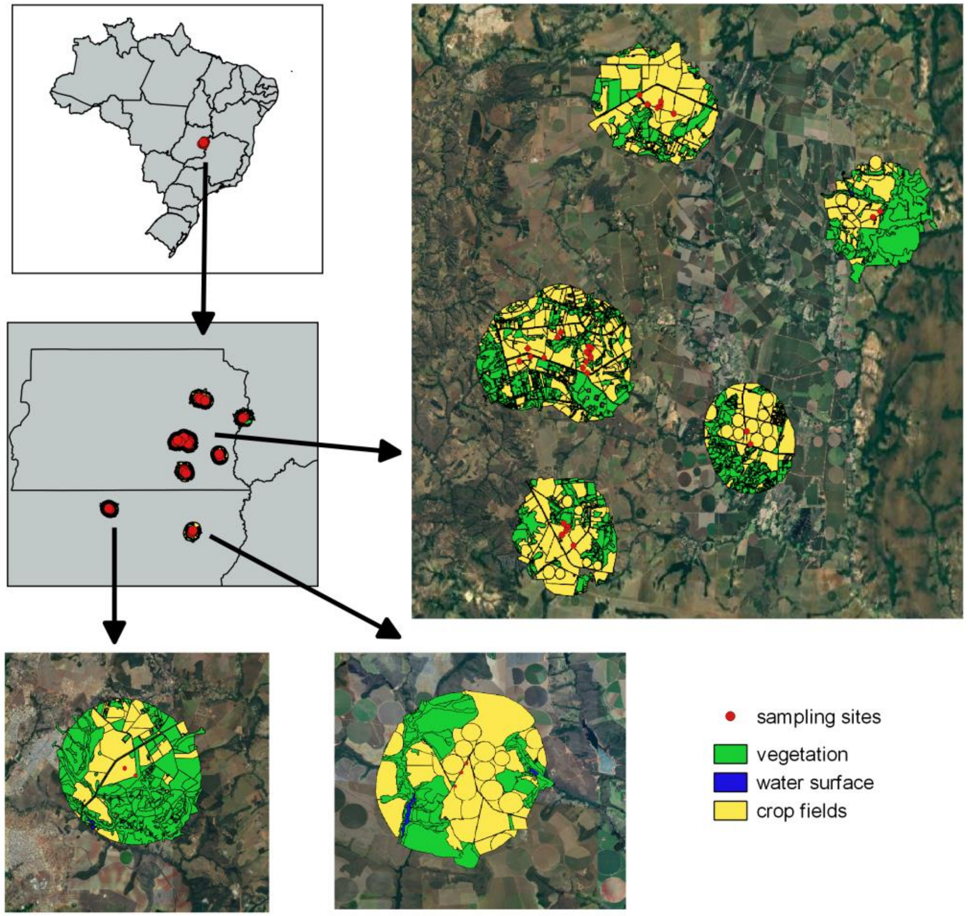

FIG. 3 – Sampling sites (35) used in this study. The study area is located in the central region of Brazil, and it is characterized by a high degree of land conversion, with large monocultures. The image provides an example of buffers (3500 meters radii) with land-use classes selected around the sampled fields.

Source: Elaborated by authors.

Data collection was carried out during crop seasons in 2015/2016 and in 2016/2017 (November-January). We managed to select 35 sampling sites within 11 crop fields that planted the same variety (BRS Estilo). Crop fields had a minimum distance of 1km from each other to ensure the presence of different wild pollinator communities between locations. Depending on the field size, we defined from two to six sampling sites per field along a gradient of distance to the natural habitat (ranging from 18m to 1152m), totalizing 35 sampling sites (27 in 2015/2016 and eight in 2016/2017). A minimum distance of 300m between locations was maintained, a distance that permit changes in crop pollinator diversity and density (CARVALHEIRO et al., 2010). All the research procedures were conducted with the landowners' permission.

In each site, we collected information on pollinator density and diversity following the methodology proposed by Vaissière et al. (2011). First we count the number of flowers and pollinator (abundance) along two parallel transects (25x1m). Data collection occurred during morning (09h00 to 12h30) and afternoon (13h00 to 16h00), maintaining an interval of three hours between surveys (so each site was sampled twice within a single day of the peak of flowering). Afterwards, insects were captured along transects, and later identified by taxonomists to estimate the richness of pollinators (number of species). Information of uncollected morphospecies, which description did not match with collected species, was also considered in richness. As the number of flowers varied among plots, then, we calculated pollinator density and diversity by dividing the abundance and richness, respectively, by the total number of flowers. For further details on sampling design and pollinator density and diversity data collection, see appendix A and Ramos et al. (2018) in annex A.

To collect data on yield and crop quality for each sampling site, 15 individual plants were randomly gathered along two parallel transects (25x1m). After desiccation of the beans (collected ca. 90 days after planting), all pods produced by the selected plant were counted (including thin pods with no beans, due to lack of ovule fertilization). The number of seeds were counted and placed in a 65º C kiln until the humidity level was below 14%, a procedure that corresponds to commercial bean processing (BRAGANTINI, 2005). The beans were then weighed and selected for quality assessment (see below).

3.2. Agricultural inputs and their management practices

The application of the framework to common bean pollination is illustrated in Figure 4. As a biophysical measure of the ecosystem services provided by the natural capital (i.e., vegetation areas that provide the population of pollinators), we considered native pollinator density (visitor per flower) and diversity (number of species per flower) of insects that occurred naturally (i.e., not managed) and behave as effective pollinators (i.e., touch the reproductive parts of flower).

Although none of the participating farmers owned or rented hives, honeybees (*Apis mellifera*) were detected on field sites. While it is unclear if they come from wild populations or from managed hives on other properties, the effect of managed bees was nonetheless tested, by, considering honeybee density (i.e., effective visits divided by total number of flowers at both transects) as a proxy for the input provide by honeybee hive management.

For management not related to pollination, we consider only the application of fertilizer input, which greatly varied across the study areas. We do not consider pesticide as a conventional practice due to the lack of information on the effect of this input on common bean yield, quality and pollinators. This is a practice usually used by farmers to overcome production deficit, positively affecting common bean nutritional aspects (ANDRADE et al., 2004). However, farmers commonly apply fertilizer dosage above than recommended dosage (MOSIER et al., 2004; farmers' personal communication). Previous studies have shown that such practice has negative effects on some pollinators (RAMOS et al., 2018). This effect is likely due to changes in quantity and quality of flowers resources (HOOVER et al., 2014; CEULEMANS et al., 2017), which affect the physiology, behavior, abundance and diversity of flower visitors (MUÑOZ et al., 2005; CEULEMANS et al., 2017). This chemical input is then appropriate to investigate the effects of the interaction between pollinator and conventional cropland management on common bean profitability. Fertilizer input data was provided by farmers and measured in nitrogen (kg/ha/season). Other chemical inputs were assumed to be similar across study fields (farmers' personal communication).

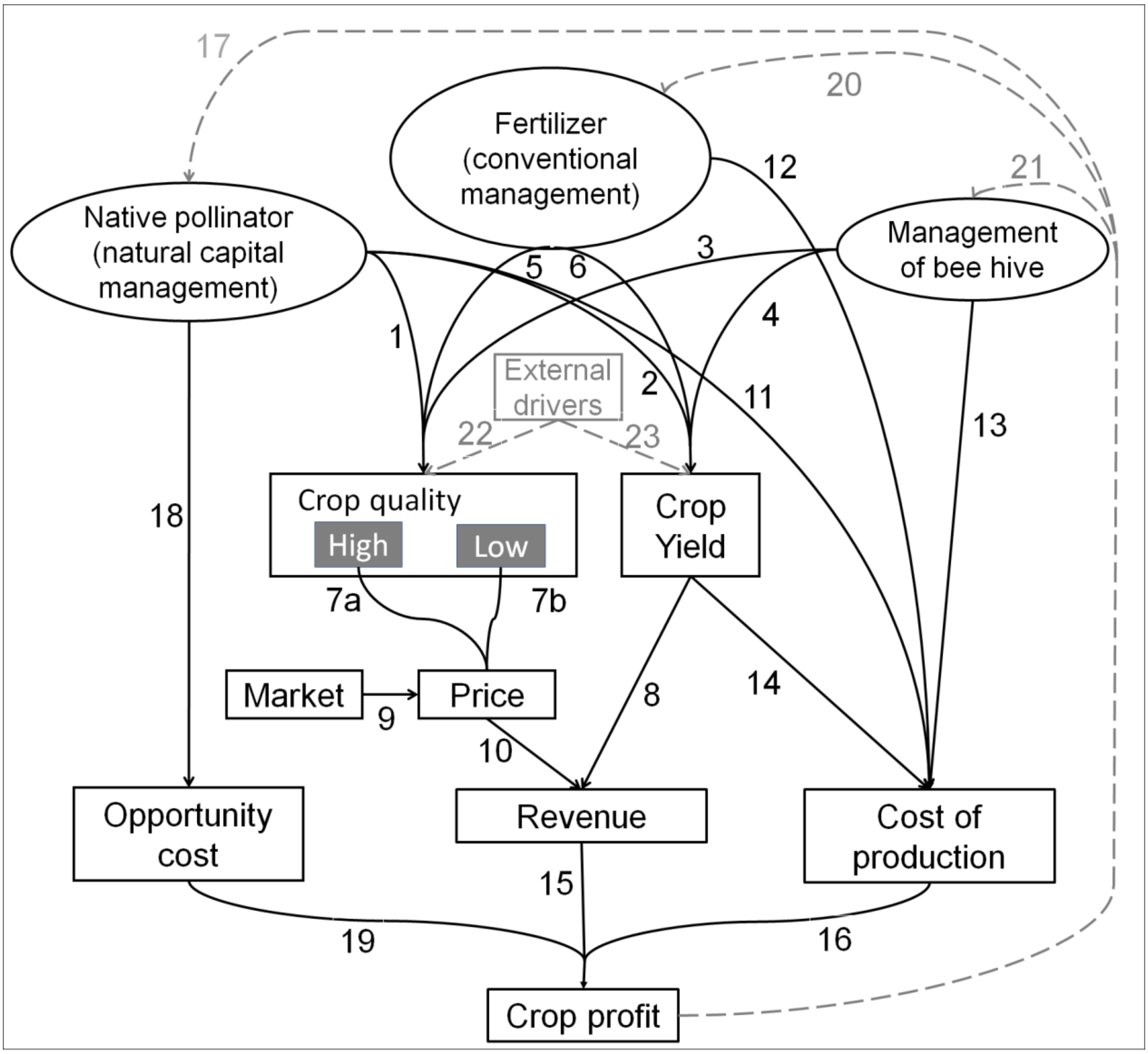

FIG. 4 – Conceptual framework for economic assessment of crop pollination at the farm scale applied on common bean production in Brazil. The bean quality classification was validated by farmers and considered to be similar to the one applied by market. Gray components indicate processes that were not included in our study case (i.e., feedbacks and external drivers).

Source: Elaborated by authors.

3.3. Effect of agricultural inputs on yield

The effect of pollinators (arrows 2 and 4 – Fig. 4) on yield can be estimated based on the increase of the number of ovules fertilized per flower (i.e., weight per pod) with density and diversity of visits, as estimated by Ramos et al. (2018). The estimated effects of both native and managed pollinators (*A. mellifera*) were extracted from Ramos et al. (2018) as well as the interactive effects with fertilizer input. Similarly, the direct effect of fertilizer input on crop yield (i.e., not mediated by pollinators, arrow 6 – Fig. 4) was also extracted from Ramos et al. (2018). All estimates were converted so that yield would be given in kg per hectare, a unit scale typically used by farmers. For conversion we used the average pod per square meter (i.e., 144 pod/m^2), which was calculated using the average number of flowers produced per plant (i.e., 30 flower/plant), the average percentage of flowers that became pods (i.e., 40%) (see MARTINS, 2017), and the average number of plants per square meter observed during crop season in our study region (i.e., 12 plants/m^2) (see RAMOS et al., 2018; Table 2).

Ramos et al. (2018) showed that common bean yield was positively associated with native pollinator density, but only under low levels of fertilizer input. However, in the case of honeybee density, there was a negative effect on crop yield, independent of the fertilizer input level. This result is likely due to robber behavior of this pollinator in common bean flower, when a pollinator collects resources with no delivery in pollination services (KASINA et al., 2009a and 2009b). Thus, honeybee management may be not appropriate to provide pollination services for this crop. The effects of native pollinator density and honeybee density were not enhanced by the diversity of wild pollinators. That information was used in our economic assessment (see below).

3.4. Effect of agricultural inputs on crop quality

To evaluate the effects of agricultural inputs on crop quality we considered two parameters which are known to influence common bean price: bean size and color (ARMELIN et al., 2007; RIBEIRO et al., 2008). From all the beans collected in the previous steps, fifteen beans were randomly selected from each sampling site. The beans were grouped into two size classes, separated by a length threshold of 10mm, following methods of the Brazilian Ministry of Agriculture, Livestock and Food Supply (BRASIL, 2008 and 2009). To assess color, farmers commonly use visual comparison, a method which we replicated. To minimize subjectivity, we selected beans that covered a range of colors found in the study region and created a scale of tonalities varying from 1 (darker) to 3 (clearer) (see Fig. 5). This scale was used as a reference to classify each of the selected beans. Both methods for assessing size and color were validated by one of the participating farmers who have a great expertise in common bean trade.

Information on size and color were then combined to classify beans of each sampling site in two quality classes used by farmers: High quality and Low quality (Box: Crop quality – Fig. 4). ‘High quality’ beans must be more than 10mm in length and have a color parameter of 3. All the others bean was considered as low quality bean. Finally, we calculated the proportion of beans in each sample that fall in each of these three crop quality categories.

FIG. 5 – Tonality scale used for the common bean. The highest number (lightest tonality) is associated with higher market price.
Source: Elaborated by authors.

A Generalized Linear Mixed Model (GLMM), assuming binomial error distribution, was then applied to assess how quality (i.e., the probability of bean being classified as high quality) was affected by each inputs associated to natural capital management (i.e., density and diversity of native pollinators, arrow 1 - Fig. 4), honeybee management (i.e., honeybee density, arrow 3 in Fig. 4) and conventional management (i.e., fertilizer input) (arrows 5 – Fig. 4). The probability of being classified as low class was calculated as 1 minus the probability of being classified on high. To take into account management interactions, we included a two-way interaction between density and diversity variables, as well as between pollinator density and nitrogen input. The GLMM was an appropriated statistical approach because it can deal with the problem of pseudo-replication (i.e., one field with two or more sampling site) that is inherent in our data set (BOLKER et al., 2008). Thus, to account for the temporally nested sampling design, ‘year’ was included as a random variable. In addition, as some participating farmers owned more than one field, we also included a ‘field’ variable within ‘producer’ in the random structure of the model. We then applied a model selection procedure based on Akaike’s Information Criterion, corrected for small sample sizes (AICc). In cases where two or more models had similar predictive power (i.e., ΔAICc < 2, considering the best model AICc as a reference), the averaged model was calculated. Average estimators reduce bias and have higher precision (BURNHAM and ANDERSON, 2002). All statistical analyses were carried out with the software R (R DEVELOPMENT CORE TEAM, 2017), using the ‘lme4 version 1.1-12’ package for GLMM (BATES et al., 2016) and the ‘MuMIn version 1.15.6’ package for model selection (‘dredge’ function) and average model (‘model.avg’ function) (BARTON, 2015). Based on the probability estimates here estimated we calculated the proportion of yield associated to each quality class

3.5. Economic assessment

All the equations extracted from the statistical analyses to test our framework, are presented in Table 2. Following the framework, we estimated revenue multiplying the proportion of yield associated to each quality class by its respective quality-adjusted price (arrows 7 a-b and 8 – Fig. 4). In 2016, the market experienced an unusual increase in crop price due to a shortage of the common bean. To avoid an overestimation in values, farmers were consulted on quality-adjusted prices typically used for each crop grade, which were: high (0.64 USD/kg), and low (0.54 USD/kg) (arrow 9 and 10 – Fig. 4). We then calculated overall revenue by summing the revenue of each of the classes.

3.5.1. Honey bee management cost

To estimate the cost associated to the management of honeybee hives (arrow 13 – Fig. 4), the implementation cost of 1 hive was considered to be 133.38 USD per month (estimate from the Beekeepers Association of Distrito Federal president, personal communication), and that 1 month would be sufficient to cover the crop blooming period. To estimate the supplemented honeybee density, we assumed that each hive has about 20000 adult bees of which 64% (12500) are adult (BEEKMAN et. al., 2004; RUSSEL et al., 2013). One third of adult bees (4167 bees) play an active role in foraging, while the remaining two thirds are dedicated to other activities, such as nursery, cleaning, building, guarding (see JOHNSON, 2010). Foragers can search for resources up to 5km (or more) away from the hive, and although foraging density declines with distance, most activity is done within 1km from the hive (COUVILLON et al., 2015, COUVILLON and RATNIEKS, 2015). We considered that, in the presence of adequate foraging resources (such as a flowering common bean field), around half of the foraging bees will forage near the hive (see COUVILLON et al., 2014). Within the common bean fields the other half is likely to forage alternative resources within that same range (e.g., natural vegetation, other crops or urban areas) (see SPONSLER et al., 2017). Thus, we estimated an increase of 2084 foraging bees per additional hive. Taking into account that, according to our research field data, common bean fields had on average 389000 flowers per hectare during the peak of blooming in our study region, each hive per hectare increases the honeybee density by 5.4 honeybees per 1000 flower.

3.5.2. Production cost

For production costs associated to agricultural management not related to pollinators (arrow 12 – Fig. 4), we considered the cost of fertilizer input, our focal variable, based on the price of urea (1 kg of urea has ca. 0.4 kg of nitrogen and cost 1.02 USD.kg^{-1} in 2015, see CONAB, 2018). All others inputs for which we had no detailed information per farm were grouped in two components: i) variable costs, which included all expenditures associated to variable input allocated in each season production, such as planting and harvesting; ii) fixed costs, which included expenditures incurred by farmers whether or not production take place (DEBERTIN, 2012), in which we assumed they were constant across fields. Variable cost was 0.24 USD per kg of production (arrow 14 – Fig. 4) and fixed cost was estimated as 226.73 USD.ha^{-1} (arrow 12 – Fig. 4) (estimated by CONAB, 2018). The final production cost per hectare was estimated as the sum of honeybee management cost, fertilizer cost, variable cost, and fixed cost.

3.5.3. Profit estimation

Profit was then calculated as the difference between revenue and cost of production per hectare (arrows 15 and 16 – Fig. 4). We estimated profit considering some assumption: first, the effect of pollination services on yield and quality is represented by a S-shaped curve, because we assume that the benefit would be saturated at some point of pollination mediated by vegetation cover; second, we assume that cropland management was based on pollination services and fertilizer management, regardless of the cropland area; and third, we also accept that the conversion of yield (g/pod) to spatial scales (m^2 and ha) can be done by using information of number of flowers and that up-scaling (m2 to ha) can be done using a linear association. All monetary values were gathered in Brazilian *Reais* (R$) and converted to US dollars (USD) using the monthly average exchange rate in 2015, as per the Brazilian Central Bank (i.e. 3.48 R$.USD^{-1}) (BACEN, 2018).

The framework applied to the common bean (Fig. 4) was reproduced with R software (R Development Core Team, 2017). Two versions of the framework in R code are available in the Supplementary Material S1 and S3. The first is a short version that can be used to estimate profitability (USD/ha) as a function of pollination services and fertilizer input. The second is an expanded version used to integrate information on how vegetation cover affect pollination services, to calculate total profit in a given farmland area, to estimate opportunity cost, and to assess the economic feasibility of investing in reforestation in order to improve pollination services. Thus, both versions can be used by others to simulate different scenarios of investment in pollination services and fertilizer input for the common bean, and adapted to others crops.

3.5.4. Simulation of investment scenarios and opportunity cost

Based on the model described above, the effect of investment in natural capital on crop profit was estimated taking into account the management of fertilizer (which affects native pollinator density) and honeybee hives. Fertilizer management scenarios were: i) Low N input, application of 45 kg of nitrogen per hectare; ii) Moderate N input, which is the application of the recommended dosage of nitrogen for the common bean in this study region (i.e., $60kg.ha^{-1}$) (see Sousa and Lobato, 2004); iii) Intensive N input, which indicates intensification of fertilizer use (i.e., 130 $kg.ha^{-1}$). For honeybee management we also considered two scenarios: i) No hives; and ii) investing in 1 hives per hectare. All estimates extracted to test the framework are presented in Table 2.

Opportunity cost is here considered as the economic benefit that farmers could gain if natural vegetation areas were used for agricultural production instead of to conserve as natural capital for crop pollination. In a cultivated area of a given pollinator-dependent crop, the conversion of natural vegetation has two main effects on production: first, it expands the cropland area; and, second, reduce pollination supply that, consequently, may reduce yield and crop quality. Previous studies showed that pollinator management at landscape level is most effective if done in a circular area of 0.5km radius, which is equivalent to an area of 78 hectares (see for diversity RAMOS et al., 2018; for abundance and diversity Chapter 2). Total profit was estimated using profitability (USD/ha), as a function of pollination services mediated by vegetation cover, and available cropland area (i.e., total farmland area minus vegetation cover). Taking into account a hypothetical farmland of 78ha, opportunity cost was assessed as the potential economic gain as a function of all cropland area (78 ha) times profitability ($/ha) estimated in a scenario with no pollination services. The effect of vegetation cover on pollination services was extracted from landscape analysis from Chapter 2.

3.5.5. Economic feasibility of reforestation for provision of pollination services

Reforestation cost was estimated so that if could be integrated in the economic feasibility assessment, taking into account varying amounts of the vegetation cover within an area of 78 ha (i.e., the area of a circular landscape of 0.5km radius). Thus, we used information on restoration cost taken from Antoniazzi et al. (2016), which assessed the cost associated to three alternatives for restoration: natural regeneration, direct seeding, and seedling planting (arrow 11 – Fig. 4). This study was carried out in eight Brazilian states, including the region of *Cerrado* biome located in four out of eight states. According to Antoniazzi et al. (2016), all these alternatives were defined because are restoration alternatives legitimated by the Brazilian Forest Code, the environmental law that regulates the management of natural areas within private owned land. The forest restoration depends on several local and specific drivers, such as, lowest cost alternative, lowest competition with others economic activities, appropriate areas for conservation, and potential forest products (ANTONIAZZI et al., 2016). The restoration cost considered here only encompass the expenditure associated to operational activities (planting and input costs), not including planning, diagnostic, monitoring, and management of the area. After considering the information above, we estimated an average cost using the natural regeneration alternative of 711.64 USD per hectare of vegetation reforested (range, 273.25 – 1168.15 USD/ha), using direct seeding alternative is 931.92 USD/ha (range, 745.86 – 1141.72 USD/ha), and using seedling planting is 4004.56 USD/ha (range, 2559.24 – 5551.91 USD/ha).

Profit (USD) was estimated by multiplying available cropland area (ha) (excluding vegetation cover) by profitability (USD/ha). Profitability was estimated with pollination services mediated by vegetation areas. Using information on reforestation cost described above, we calculated the total cost of reforestation for different levels of vegetation cover in a farmland area of 78 ha considering the optimized vegetation cover as a reference for reforestation management.

In our economic assessment, we assume that a given farmer will use only common bean in cropland area. A more realistic analysis could include the rotation of crops, but we had no information on how others crops would behave in terms of profit mediated by pollination services. Consequently, in this study, cash flow for economic feasibility assessment had only two components: i) cost of reforestation in the first period; ii) profit for each year considering two plantation seasons per year.

In our assessment, increased profit only occurred when reforestation are in a stage that provide pollination services. Previous studies found that floral planting on marginal areas of crop fields offer pollination services at five years (see BLAAW and ISAACS, 2014; PYWELL et al., 2015). Afterwards, we assumed natural and reforested vegetation areas provide continue flow of pollination services while common bean production take place.

Finally, we used two economic indicators to present the results of the economic assessment of restoration practices: Net Present Value (NPV), and Payback. The first indicates the present value of the reforestation project, which is only considered to be feasible if this value is positive. The discount rate (d) was estimated based on the average interest rate during 2015 and 2016 (period of research field) (i.e., 6.88%) of the Brazilian Constitutional Found of Financing of Midwest Region (*Fundo Constitucional de Financiamento do Centro-Oeste* – FCO Rural), a financial program to support the rural production. As we cannot be sure how long farmers would practice such activity, we assume here that this case represent a perpetual cash flow scenario with constant value for profit per year. Thus, the equation used for net present value was NVP = (Profit/d) (SAMANEZ, 2010). The second indicates number of years that this project requires to compensate the reforestation cost by the benefits received from pollination services. The integration of opportunity cost and economic feasibility assessments was done using the electronic version of the framework in R code presented in Supplementary Material S3 – Chapter 2.

Table 2 – Equations used to apply the framework to the common bean case study. Ramos et al. (2018) applied the transformation log(Y/(2-Y)) on yield and we apply the same transformation on crop quality variables to represent a sigmoid function (s-shape). The models include natural capital management via native pollinator density (NC1) and diversity (NC2), managed bees via honeybee density (MB), and nitrogen input management (N). Prices ($USD.kg^{-1}$) were: 0.64 for high quality (HQ), 0.54 for low quality (LQ). The average number of 144 pod per m^2 was used to convert estimated yield ($\hat{Y}$) in $kg.ha^{-1}$.

Input	Equations
Yield Model $\hat{Y}$=[2/(1/exp(Y)+1] ($g.flower^{-1}$)	-1.32+0.016*N-45.1*MB+(638.5-6.8*N)*NC1
High quality (HQ') HQ'=[0.68/(1/exp(HQ)+1]	-1.77-0.00036*N-11.74*NC2+(3088-30.39*N-25330*NC2)*NC1
Low quality (LQ)	1 – HQ'
Revenue (R) ($USD.ha^{-1}$)	(0.64*HQ'+ 0.54*LQ)*(($\hat{Y}$*144*10000)/1000)
Production Cost PC) ($USD.ha^{-1}$)	64.66+0.45*2.5*N+10900*MB+0.24*(($\hat{Y}$*144*10000)/1000)
Profit (PF) ($USD.ha^{-1}$)	R – PC

Source: Elaborated by authors.

4. Results

4.1. Effect of crop pollinators on common bean yield and quality

Estimates of the effect of native pollinator density, honey bee density, nitrogen fertilizer and pollinator diversity on crop yield were obtained directly from Ramos et al. (2018) (see Table 2). Ramos and collaborators (2018) found that common bean yield (g/pod) was positively associated to native pollinator density under intermediate fertilizer input. In addition, honey bee density presented a negative effect on crop yield, probably due to its robber behavior, and diversity had no effect on yield.

The present study results show that variation in common bean quality was partly explained by crop pollinators and fertilizer application (see Table 3 and Figure 6). The results showed that, under a high diversity of pollinator species and nitrogen application, density of native pollinators increase the probability of a given seed of being classified as high quality. Managed bees presented no effect on the probability of high quality bean. Thus, similar to common bean yield analysis, crop quality here was mostly influenced by native pollinator density and nitrogen application. The estimates used for quality analyses are presented in Table 2.

Table 3 – Effect of natural capital on common bean quality assessed with the following explanatory variables: density of native pollinators (NC1), diversity of pollinators (NC2), honeybee density (MB), and nitrogen input (N). The symbol '*' represents a two-way interaction and 'X' indicates the inclusion of the variable in the model. Full average model was based on models that presented a variation lower than 2 (ΔAICc) in the Akaike Information Criteria adjusted for small sample sizes (AICc). Maximum percentages of high quality observed in sampled seed were 0.68.

Models	Explanatory variables								weight	AICc	ΔAICc
High quality (probability)	NC1	NC2	MB	N	NC2*MB	NC2*NC1	N*MB	N*NC1			
First model	X	X		X		X		X	0.360	177.8	0.00
Second model	X			X				X	0.144	179.6	1.83
Full average model	log(Y/(0.68-Y)) = -1.77-0.00036*N-11.74*NC2+(3088-30.39*N-25330*NC2)*NC1										

Source: Elaborated by authors.

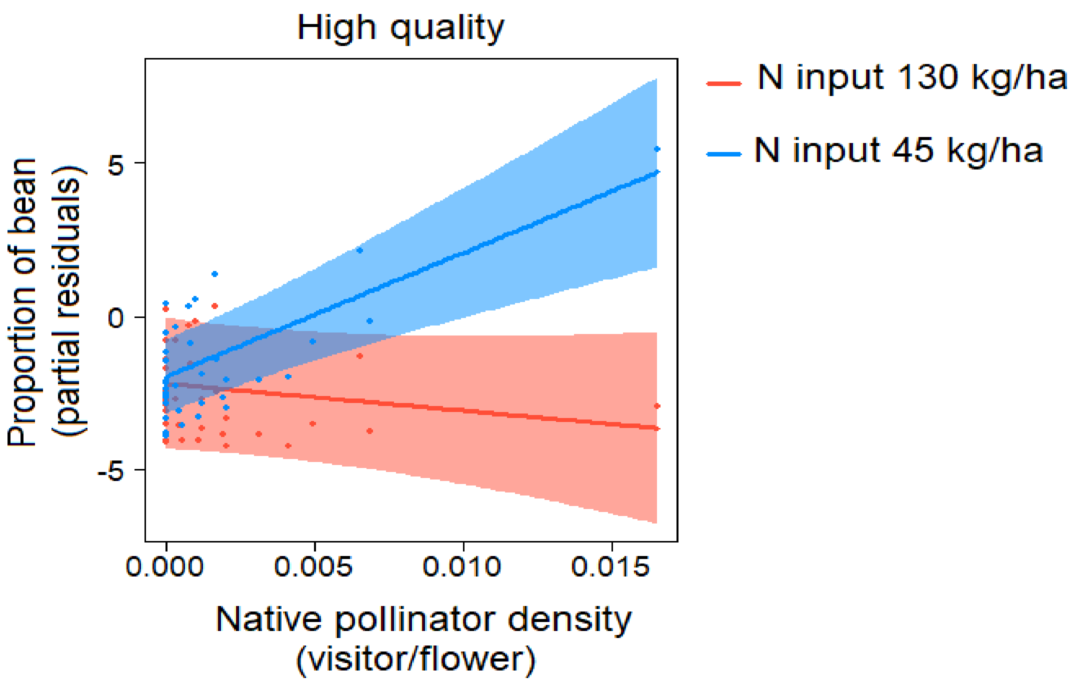

FIG. 6 – Effect of natural capital management (native pollinator density) on common bean quality. Graphics depict first models from table 3. Shaded areas represent confidence interval of 95%, and, dots indicate the observations. Response variables were Log-transformed for normalization of errors. Maximum percentage of high quality observed in sampled seed was 0.68. Native pollinator density represents the abundance of pollinator per flowers.

Source: Elaborated by authors.

4.2. Effect of crop pollinator management on common bean profitability and profit

To assess the effect of pollination services input on farmers' economic output, we estimated profitability (USD/ha) using two scenarios of honeybee management: i) investing in one hive per hectare; and ii) no hives. In addition, we also assessed the scenario with three levels of nitrogen input (i.e., 45, 60 and 130 kg of nitrogen per hectare). Intermediate levels of nitrogen input, or lower, (i.e., <60 kg/ha) positively influenced the effect of native pollinator density on farmers' profitability in common bean production, regardless honeybee hives management (Figure 7). At highest level of nitrogen input (i.., 130 kg/ha), farmers' profitability was negatively associated to native pollination density. Thus, under the recommended dosage of nitrogen input scenario, common bean profitability (USD/ha) is positively associated to natural capital (i.e., native pollinator density), independently of honeybee hives application. This scenario indicates a potential management strategy for common bean pollination.

To assess the trade-off of farmers associated to which percentage of vegetation cover could be conserved to maintain economic benefits with pollination services, we estimate profit in a hypothetical farmland area of 78ha. Taking into account a scenario of variation of vegetation cover from zero up to 60% (vegetation cover that maximizes economic output) in a farmland area of 78ha, total profit increased from 7504 USD up to 18985 USD (Figure 8). This trend occurred because the increased profitability due to pollination services was higher enough to compensate the restriction in cropland area. After, estimated profit presented a negative association with vegetation cover.

4.3. Opportunity cost and economic feasibility of natural capital management

Benefits of natural capital (i.e., the increase in native pollinator density) was most accentuated when no managed bees were used and with intermediated application of nitrogen (i.e., 60 kg/ha of nitrogen) (Figure 7). Opportunity cost was then calculated multiplying all farmland area (i.e., 78 ha) and the profitability (96 USD/ha) associated to no provision of native pollination services (i.e., 7488 USD) (Figure 8). Estimating profit in a scenario with no honeybee management and the application of intermediate level of nitrogen input (i.e., 60 kg/ha), nature conservation may be profitable for farmers until 87% of vegetation cover, because opportunity cost was higher than common bean profit associated to pollination services only in cases of percentage level above of such threshold (Fig. 8).

To assess the economic feasibility of natural capital management via a reforestation project, we simulate the variation in total profit due to increasing in vegetation cover up to 60% (vegetation cover that maximizes economic output – Fig. 8) in such farmland area of 78 ha. Net present value and payback was calculated for each scenario of vegetation cover (i.e., from 0 to 60%) using three alternatives with different associated costs (i.e., natural regeneration, direct seeding, and plantation of seedlings) (Fig. 9). Natural regeneration and direct seeding presented a similar net present value and payback, despite the fact that the first management approach was less expensive. Net present value considering natural regeneration and direct seeding technics were positive, indicating that reforestation up to 60% of vegetation cover is a feasible alternative in all scenarios of vegetation cover. For planting of seedling technic, net present values was positive, but lower than others alternatives for reforestation. In addition, the time to compensate such investment (payback) considering the enhanced profit with pollination services was nearly 18 years, whereas for direct seeding and natural regeneration, payback was less than 5 years, respectively.

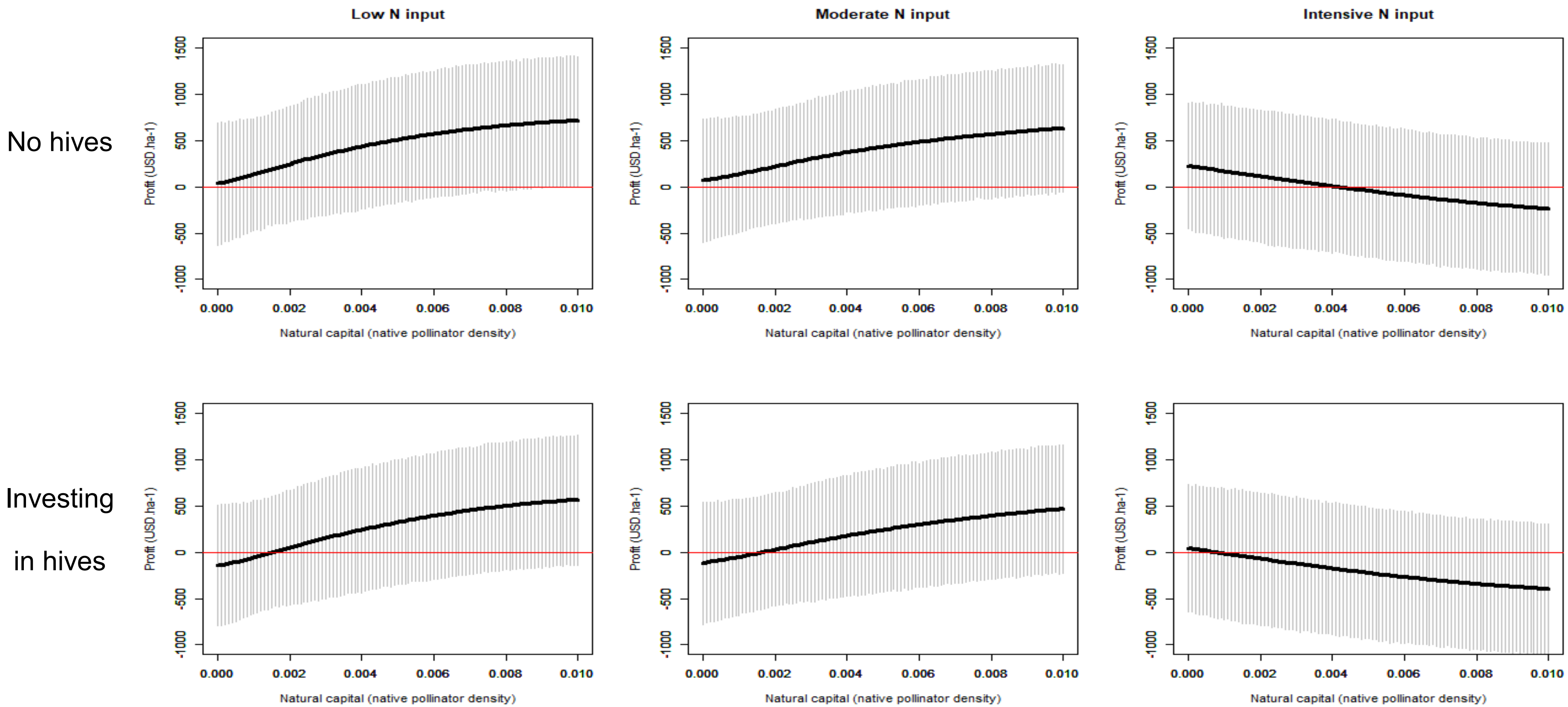

FIG. 7 – The effect of natural capital (native pollinator density – visitor per flower) on common bean profit taking into account management of fertilizer (Ninput) and honeybee hives. Low, Moderate and Intensive N input scenarios indicate application of 45, 60 and 130 kg of nitrogen per hectare, respectively. Investing in hives scenario indicates the management of one honeybee hive to supplement the pollinator density in 0.0054 honeybees per flower (see Supplementary Material S1). Shaded area represents 95% confidence interval and 'red line' indicates zero value for profit. Opportunity cost was not included in those estimates.
Source: Elaborated by authors.

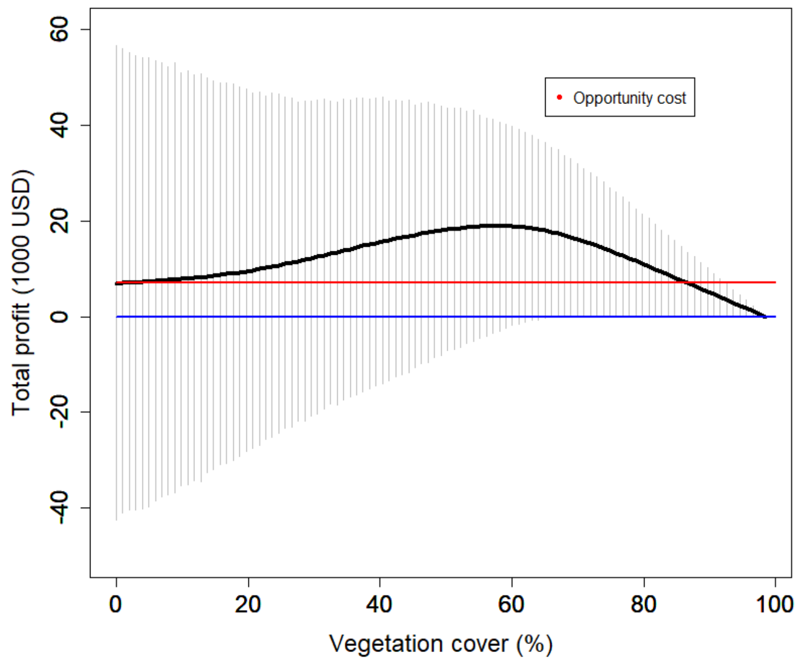

FIG. 8 – The effect of opportunity cost on common bean profit. Estimates were done taking into account the native pollinator management via natural capital conservation, no investment on honeybee hives, and nitrogen application of 60 kg/ha for fertilizer management. Total profit was estimated in a hypothetical farmland of 78 ha (i.e., an appropriate area for pollinator management at landscape level) considering the available cropland area as a result of total area minus vegetation cover. Opportunity cost (7488 USD) was estimated multiplying the profitability in a scenario with no pollination services (i.e., 96 USD/ha) by the total farmland area (78 ha) (see Supplementary Material S3). Shaded area represents 95% confidence interval and ‘blue line’ indicates zero value for profit.
Source: Elaborated by authors.

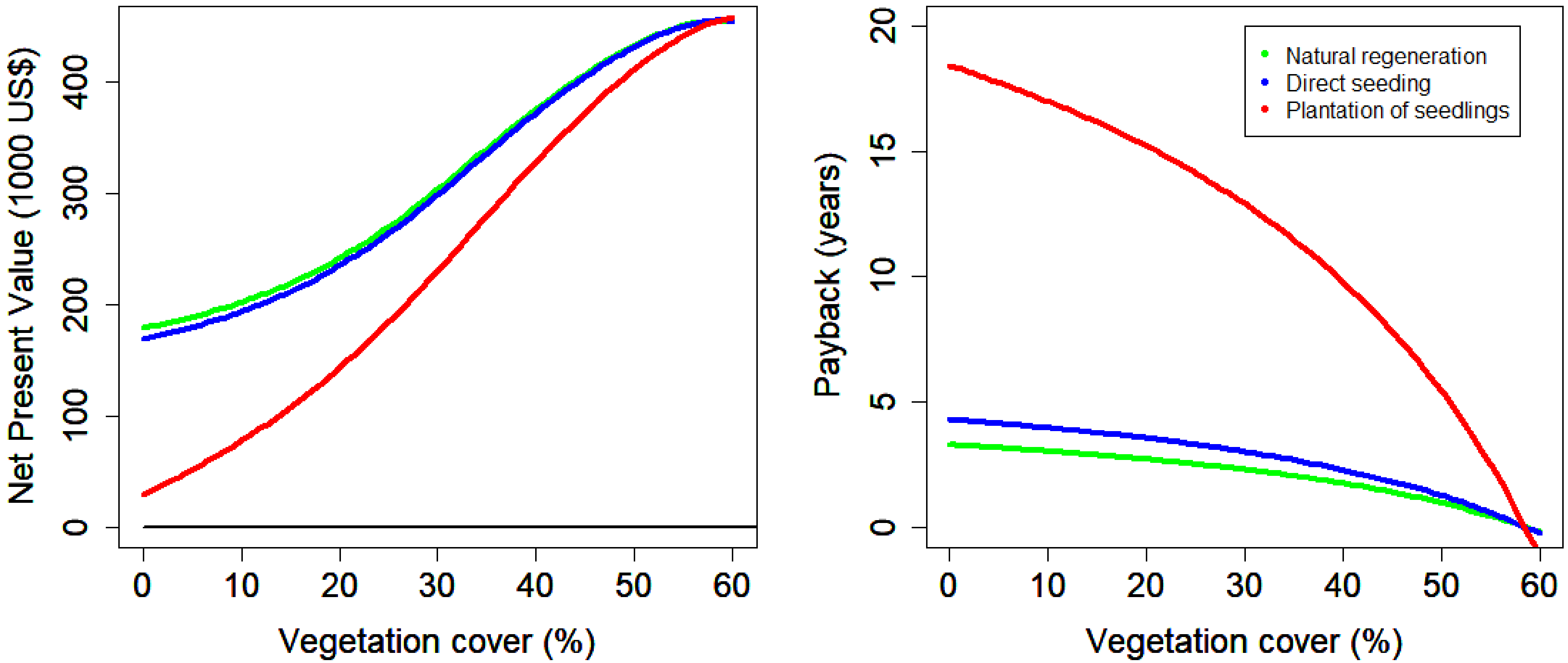

FIG. 9 – Net Present Value and Payback (years) of the reforestation project when applying three different reforestation technics (natural regeneration, direct seeding, and plantation of seedling) with increasing vegetation cover. Reforestation was always done so that 60% of vegetation is achieved. Estimates were obtained assuming a farmland area of 78ha. Maximum vegetation cover allowed by the simulation was 60%, so that at least 40% of the land is used for crop plantation. For example, a graphs show that for a farmland with currently 20% of vegetation cover, reforestation up to 60% using the direct seeding method will lead to a net present value of nearly 200.000 US$ and a payback (time for compensation) of about 4 years considering.
Source: Elaborated by authors.

5. Discussion

Detailed economic valuation of benefits associated to ecosystem services at the farm level is essential for landowners to better recognize the advantages of investing in sustainable farming practices. This study showed investing in natural capital can enhanced common bean profit via pollination services. Such economic output is due to increased yield and crop quality due to pollination services, which are influenced by the fertilizer application. Below we discuss the implications and limitations associated to our findings and evaluate the usefulness of the presented framework for sustainable management practices in agricultural systems worldwide.

5.1. Effect of pollinator on common bean yield and quality

Ramos et al. (2018) found that common bean yield is positively influenced by native pollinator density under intermediated levels of fertilizer application. Similar interactive effects between nitrogen availability and pollinators have been reported for others crops, such as almonds (BRITTAIN et al., 2014), sunflower (TAMBURINI et al., 2017), and oilseed rape (MARINI et al., 2015). Fertilizers increase the nitrogen availability, influencing the investment strategy of plants between reproductive and vegetative development (RUSCH et al., 2013). Under lower nitrogen levels, common bean flowers tend to be more abundant (RAMOS et al., 2018). Moreover, in average, 40% of the common bean flowers became productive pods (MARTINS, 2017), being this process influenced by external drivers (i.e., biotic and abiotic factors). Thus, if these drivers were constant, reducing nitrogen availability, which may increase the number of flower, associated with pollination services may enhance crop yield in common bean production. This indicates that the optimized use of chemical inputs can also be a management strategy for pollination service that improves farm benefits.

The positive effects of pollinators on common bean color and size (two traits relevant for bean market price) here detected, give strength to the idea that assessing effects on quality is essential to fully assess the value of natural capital. Common bean traits, as any other living organism, are defined mainly by additional genetic effects that are influenced by the interaction between several genes (MOTTO et al., 1978; CORTE et al., 2010). Genetic flow (i.e., the transfer of genes between individual of the same species via gamete dispersion) in common bean is described as low (PINHEIRO and FARIA, 2005). This is likely due to the fact that most farms are large and gamete vectors (i.e., pollinators) are mostly absent. Farmers commonly select seeds to control the quality aspects that are valuable at markets, so bigger seeds with lightest tonality are preferable to be sow, but the reduction of genetic variability may propitiate the reduction in crop quality (see Table 1). Such effects might be more accentuated for traits that are controlled by a complex of genes with additive effects, such as seed size in common bean (CORTE et al., 2010). In addition, this trait influences the presence of polyphenols (i.e., tannin) in common bean seed, a micronutrient associated to the darkening process of seeds (BRESSANI et al., 1988; IADEROZA et al., 1989). This genetic link between the two traits here studied explains why both were similarly affected by pollinators. Thus, crop pollination is a service with a great potential for the intensification of genetic flow that may end up improving common bean quality.

5.2. Effect of pollinators on overall profit of common bean

Common bean profit mediated by pollination services greatly varied in our study due uncertainties associated to how landscape is providing such services and how it is affecting productivity and crop quality. Homogeneous landscape largely covered by crop fields has two effect on pollinators and its services: first, mass-flowering crops mostly benefit generalist pollinators (e.g., *Apis mellifera*) and their pollination services at cost of native pollinators; second, massive bloom of such crops also dilute pollination services and its benefits (KOVAC-HOSTYANSZKI et al., 2017). Both effect affect productivity per pod that was estimated having a greatly variation in scenarios with high pollinator densities (0.0165 visitors per flower) compared to no pollinator scenario presented a growth of 143% (0.82 vs 2.01 g/pod) (RAMOS et al., 2018). In addition, pollination services also influenced the percentage of high quality bean that increased from zero (i.e., in no pollination scenario) up to 68% (i.e., high pollination supply), and this crop grade was associated to a higher market price compared to low quality bean (i.e., 19% higher).

We recognize that our results are associated to a specific situation (i.e., we assume that all other inputs are maintained constant). Large crop fields may present a profitability higher than our estimated (i.e., 96 USD/ha in a farmland area of 78ha with no pollination services) because farmers would vary the others inputs, for instance, application of more fertilizer and pesticides, modified seeds, irrigation, among others. In addition, maximum benefit directly linked to pollination services could be assessed via hand pollination and exclusion treatments. Thus, estimated farmers' profit was associated to great variation in pollination services that is difficult to find in real field conditions (e.g., 80% of vegetation cover). However, our study demonstrates how farmers' profit is associated to pollination services, how such services can be managed to maximize this benefit by also considering its cost, and that important trade-offs between investment in conventional farming practices (i.e., fertilization) and natural capital management practices do exist and can have strong effects on final farmer profit.

Previous works reported benefits of pollination supply in crop yield and profit (WINFREE et al., 2011; HANLEY et al., 2014). By applying an economically detailed framework we quantified in detail the actual benefit under different levels of investment in pollination service. We also demonstrated that the economic output of such investment can be strongly dependent on the effect of pollinators on crop quality and on how farmers manage fertilize input. Overall, the proposed framework allows to identify the best managing practices of ecological intensification, by integrating ecosystem services into cropland management plans, balancing ecological and economic interests. Finally, opportunity cost assessment indicated that natural capital management can bring ecological and economic benefits for common bean production and its attractiveness is dependent on which technic for reforestation is more appropriated.

Although our model may not correctly reproduce the behavior of profit below the minimum levels of nitrogen input that fed our statistical analyses (i.e., <36 $kg.ha^{-1}$), we are able to conclude that common bean profit (USD/ha) only responds positively to native pollinator under intermediates levels of nitrogen input (i.e., 60 to 80 $kg.ha^{-1}$). In the study region, common bean farmers usually do not consider the preservation of natural habitat as a strategy to manage crop yield, instead it, the existing fragments of natural habitat on their properties are maintained in adherence with Brazilian environmental laws. Also, they typically invest highly in conventional intensification (chemical input and extensive cropland), which can lead to farmers applying more nitrogen than the recommended dosage for common bean in this study region (i.e., 60 kg/ha) (see SOUSA and LOBATO, 2004). The results presented here may guide future practices that optimize the use of chemical inputs and potentially simulate the inclusion of ecosystem services into cropland management plans.

The honeybee, an exotic species found in our study region, can easily be managed by farmers. However, the effect of native pollinators on common bean profit (USD/ha) was independent on investment in honeybee hives. This effect is likely due to the honeybee's robber behavior, whereby they collect resources but do not pollinate common bean flowers (KASINA et al., 2009a and 2009b; RAMOS et al., 2018).

5.3. Expanding horizons: applicability to other crop systems

Different crop systems will have different susceptibilities to pollinators and to the chemical inputs considered here. For example, honeybees are known to contribute effectively to the pollination of a large number of crops, such as pumpkin, coffee, mango, grapefruit, among others (GARIBALDI et. al., 2013), and they may even have beneficial synergistic effects when acting together with wild native bees (CARVALHEIRO et. al., 2011). In addition, other inputs and other potential interactive effects between chemical inputs and crop pollinator supply may be interesting to add to economic evaluations. The framework proposed here can be used in further studies as guidance to incorporate the additional effects for other crop systems, and hence be used to estimate profit variation under these interactive effects.

In our case study, we used the framework to estimate the profitability in one hectare of common bean. To take into account all cropland area, so an adaptation in the proposed framework was required. The analysis at landscape level allowed the integration of opportunity cost (i.e., associated to nature conservation) and natural capital management cost (i.e., restoration of vegetation). For this situation, it is important to integrate the variable distance from native vegetation, which could improve the profit estimates here presented. Moreover, this framework can be adapted to other ecosystem services that contribute to the availability of a product on the market (e.g., water supply, biological control, soil conditions, among others) (DIETZE et al., 2019). Lastly, future studies may investigate how the economic benefits of pollinators interact with other ecosystem services and other conventional management practices (BOMMARCO et al., 2013; DARYANTO et al., 2019). Our electronic version in R Code (Supplementary Material S1) can be an important tool for future studies.

5.4. Implication for biodiversity conservation

The framework proposed in this study is intended to support local management planning, and can motivate landowners to use practices that are both profitable and sustain natural capital. Natural capital supports numerous other ecosystem services that benefit human well-being from the local (e.g., soil preservation, water resource maintenance) to the global scale (e.g., air purification, carbon sequestration and climate regulation) (MEA, 2005). In addition, pollination services also contribute for food security (EILERS et. al., 2011). Consequently, the framework proposed here is of importance not only to farmers, but also to consumers and governance institutions. By integrating information on vegetation cover, our study contributed to the potential application of economic instruments that aim to improve attractiveness of conservation by farmers. Recognizing these benefits can thus promote the creation of instruments that enforce the maintenance of ecosystems on private properties, such as conservation of target areas for pollination protection.

Economic instruments that recognize the positive externalities of natural capital (e.g., pollination of neighboring fields, carbon sequestration, and air purification) may increase the attractiveness of environmentally-friendly practices, such as Payment for Environmental Services (PES) programs, and may be easily integrated into the framework by a component in the ‘Revenue’ box (Fig. 1). In addition, such instruments are applied only in those cases where natural areas protected exceed a given baseline defined by environmental laws (Principle of Additionality). Thus, the inclusion of natural capital in cropland management must to ensure the minimum conservation area for the environmental regulation compliance plus an additional area for both pollinator management and economic gains with positive externalities. Other example of economic instrument is the certification of products produced under friendly-pollinator management, which would increase the crop price at market when consumers are willing to pay (TREEWEK et. al., 2006). Overall, the framework makes a contribution to environmental policy and planning, as it can demonstrate to farmers and decision-makers how such economic instruments will benefit farm profitability, which could promote conservation and sustainable practice on rural properties.

Nature conservation restricts cropland area and overall production at the farm level and can engender externalities, such as the displacement of extensive land practices elsewhere (WU, 2000; SIMPSON, 2014). An example is the Brazilian Forest Code that enforces landowners to conserve a percentage of natural vegetation, i.e., 80% on private properties located in Amazon and 20% in the rest of the country (see SOARES-FILHO et al., 2014). Because this is calculated based on the total land owned, a landowner with two properties can remove all natural habitats on the land that is most suitable for agriculture, while leaving the another property preserved to compensate (e.g., in an area less suitable for agriculture). Enforcing conservation of target areas for pollinator protection is especially needed in regions with intensive agricultural activity, such as the Brazilian *Cerrado*, where this study was conducted. It is a hotspot biome where 40% of the remaining vegetation can still be legally converted to other land uses (STRASSBURG et al., 2017). Thus, the framework can help to inform both farmers and public agents on the cost and benefits associated to local natural capital conservation, which has been considered a bottleneck for the effectiveness of some environmental programs (LIU et al., 2008; EHRLICH et al., 2012). In chapter 2, we integrated an economic instrument that can increase the attractiveness of conservation practices by farmers using the proposed framework.

6. Conclusion

The economic benefits associated to the increase of pollination ecosystem services, as demonstrated for common bean, highlight the importance of integrating natural capital into conventional cropland management plans. Although natural capital provides several important ecosystem services, vegetation areas are considered by many farmers as a restriction of cropland areas and profit. Natural capital management can be a great alternative to enhance farmers' profit via ecosystem services, but the economic feasibility occurs in some circumstances associated to how such capital is managed. The proposed framework can be used to guide the inclusion of ecosystem services as an agricultural input into future management on privately owned land. In addition, benefits received from ecosystem services are influenced by conventional management practices, so regulation to reduce chemical inputs or to stimulate ecological intensification practices, for instance, can be an important first step toward ecological intensification. Without disregarding the importance of command-and-control regulation established by environmental policies, economic benefits could encourage voluntary shifts toward pollinator-friendly practices improving the likelihood that privately-owned fragments of natural habitat will be preserved, thereby benefiting biodiversity and human livelihoods.

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Supplementary Material S1

R codes to run the framework.

Dataset

https://github.com/lipeconomia/Material-suplementar

CAPÍTULO 2 – Nature conservation policies may increase farmers' profitability via pollination services[3,4]

Abstract

Natural vegetation in private owned lands is fundamental for biodiversity and its associated services. Conservation of such areas is difficult because conserved land is perceived by farmers as a major opportunity cost and unfair that such a cost is individualized whereas ecosystem services can benefit humanity as a whole. However, it's unclear under what conditions environmental laws may bring economic benefit to farmers, considering ecosystem services and economic compensation. Using the case of crop pollination as a biodiversity-based ecosystem service and Brazilian Forest Code as the environmental policy framework, we evaluate how current conservation policies in private owned land can bring economic benefits to farmers. Using landscape data on common bean (*Phaseolus vulgaris L.*), we assessed the effect of two target areas (i.e., Legal Reserve, which is a minimum percentage of vegetation preserved inside properties, and Permanent Preserved Areas, which are some specific sensitive areas that farmers must to conserve) on pollination agents and farmers' profitability. Using information on an economic instrument of compensation (i.e., Environmental Reserve Quotes), we estimated the total profit also considering pollinations services. Our results show that, even if landowners do not receive any environmental compensation payment by preserving more natural areas than those defined by Brazilian environmental laws, they have great economic benefits associated to pollination services. Legal Reserve and Permanent Preserved Areas maintain economic benefits for farmers and ensure the sustainability in agriculture. In addition, governmental recognition of the role of crop system not only as a producer of agricultural products but also as a provider of ecosystem services is important for the adoption of environmentally-friendly practices to protect natural capital.

Key-words: Environmental policies, Brazilian Forest Code, Legal Reserve, Permanent Preserved Areas, Crop pollination.

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[3] This research was registered in the Brazilian National System of Management of Genetic Heritage and Associated Traditional Knowledge (SisGen) (nº A7A0D07).
[4] The co-authors in the future publication of this paper are Frédéric Mertens, Davi de L. Ramos e Luísa G. Carvalheiro.

1. Introduction

Biodiversity decline puts at risk important ecosystem services (OLIVER et al., 2015) and the preservation of patches of native vegetation is one of the most effective practices to protect biodiversity and associated ecosystem services (MARGULES and PRESSEY, 2000). In many countries the majority of remaining patches of natural vegetation are within private owned land (SOARES-FILHO et al., 2014; KAMAL et al., 2015). Although evidences of benefits of natural areas to cropland productivity do exist (CHAPTER 1), most landowners have transformed native vegetation in cropland or pasture to increase profit (RAYMOND and BROWN, 2011). For example, some conflicts between farmers and governmental institutions are emerged due to conservation regulation (production of cocoa in Ghana, palm oil in Indonesia, coffee in Vietnam, and soybean in Brazil (see CONSERVATION INTERNATIONAL, 2004; TREWEEK et al., 2006). Thus, most farmers are not engaged into conservation actions, especially due to cost for nature conservation is individualized whereas ecosystem services are likely to benefit several farmers, creating positive externalities.

Nature conservation policies are also crucial to maintain biodiversity and associated services. Crop pollination is an example of such services that is important for 75% of the major world crops (KLEIN et al., 2007), and it is under threat especially due to landscape simplification (KLUSER and PEDUZZI, 2007; POTTS et al., 2010). Although managed bee can partially contribute to yield in many crops, pollination played by wild pollinators is more efficient in several crop systems (GARIBALDI et al., 2013). Different species of pollinators have different habitat requirements, for instance, some prefer areas which are naturally more forested while others require more open habitats (ISHARA et al., 2011; ANTONINI et al., 2016). Pollination services supply is benefited by increasing the percentage of vegetation areas (CONNELLY et al., 2015) and landscape heterogeneity within rural properties (ANDERSSON et al., 2014; HIPÓLITO et al., 2018). Thus, a strategy for conservation would benefit from having information on quantity and quality of natural areas that are more appropriate to provide pollination services. Previous studies focused on how pollination services mediated by landscape management affects farmers' economic by considering the percentage of natural habitat (MORANDIN and WINSTON, 2006); and the distance to natural habitat (OLSCHEWSKI et al., 2006; RICKETTS and LONSDORF, 2013). Moreover, Blaauw and Isaacs (2014) assessed the benefit provided by pollination services mediated by wild-flowering plants seeded on edge of crop fields and found that the attractiveness of such pollinator-friendly practice is enhanced via subsides on farming cost. However, such studies focused on benefits in terms of yield, neglecting the importance of crop quality for economic output (see GARRATT et al., 2014; CHAPTER 1). In addition, increased pollination services by nature conservation may also benefit crop production of others local farmers, creating positive externalities.

Externalities represent external impacts stemmed from a given activity that affect other agents (MUELLER, 2012). Such impacts can increase the benefit or cost of other agents. For example, reforestation may increase pollination service supply for neighboring fields, benefiting crop production (positive externalities). Another example is when deforestation decreases population of pollinators, negatively affecting others famers (negative externalities). In addition, internalization of such externalities can be done via transfer of both benefit and/or cost between agents (MUELLER, 2012). Environmental policies generally adopt the Principle of Additionality, i.e., economic compensation is granted only for farmers that surpass their obligation in conservation practices. In addition, farmers that do not compliance environmental laws pay for those economic compensations. The definition of compensation instruments requires information on biodiversity and land assets (CROSSMAN and BRYAN, 2009), the understanding of the institutional environment of farmers (RAYMON and BROWN, 2011), as well as, a cost-benefit assessment of the nature conservation implementation (NAIDOO et al., 2006). Internalization is crucial to stimulating sustainable use of ecosystem services, because such distortion in benefit/cost distribution may create conflicts between farmers and the government. Moreover, it is unknown under what conditions conservation policies can bring economic benefit to farmers via internalization of externalities.

Economic instruments and regulation were two main strategies adopted by environmental laws. Economic incentives are attractive mechanisms to internalize positive externalities and encourage farmers to get involve in conservation action, for instance, payments for environmental services (PES) (ENGEL et al., 2008). For example, Agri-environmental policies generally aim to change the farmers' behavior economically encouraging farmers to repair the environmental damage resulted from farming practices (DONALD and EVANS, 2006; KLEIJN et al., 2011; SCHEPER et al., 2013; BATÁRY et al., 2015). However, command-and-control regulation offers an alternative way for conservation by enforcing farmers to protect a given target area (KAMAL et al., 2015). An example is the case of the Brazilian Forest Code that obligates landowners to maintain or restore a given percentage of a specific natural area within their rural property (SNOO et al., 2013; SOARES-FILHO et al., 2014). Both "stick and carrot" strategies and a way to increase their effectiveness depend on how their combine can optimize farmers' benefits. Taking into account that costs and benefits information for conservation actions are missing in several environment policies (LIU et al., 2008; EHRLICH et al., 2012), it is important to assess how farmers will profit via pollination services and internalization of those positive externalities.

This paper aims to evaluate if current conservation policies in private owned land are bringing economic benefits to farmers. Firstly, we assessed if current conservation policies (which focus on conservation of specific natural areas at landscape level) enhance the abundance and diversity of pollination ecosystem service agents in cropland (objective 1). Secondly, we assessed how conservation practices may influence farmers' profitability via pollination services (objective 2). Thirdly, taking into account that increasing conservation areas restricts cropland, we estimate the variability in total profit of farmers considering the enhanced profitability and economic compensation of positive externalities (objective 3). We expected that both pollination services and the internalization of positive externalities compensate the decline in farmers' profit due to cropland restriction. The results of this study may help to guide future strategies for the management of conservation areas in crop systems.

2. Method

2.1. Study System

This study focused on common bean (*Phaseolus* vulgaris), an important crop for food security and the economy for Brazil, representing 12% of the total value of all annual crops produced nationally (SOUZA and WANDER, 2014; IBGE, 2016). The selection of this crop was also to the fact that we had detailed information on the benefits from pollination services in terms of yield (RAMOS et al., 2018) and quality aspects (see CHAPTER 1). This crop is produced at several landscape contexts ranging from heterogeneous to a more simplified landscape, and hence it is an interesting focus crop to evaluate potential effects of changes in landscape. Our research focused on the cultivar “BRS Estilo” (commercially known as “carioca”), which is largely produced and consumed in Brazil (MELO et al., 2009).

Private owned lands were located in the rural zone of the states of Distrito Federal and Goiás (Brazil) (see Figure 10). All properties are owned by non-family farmers that conventionally manage their cropland areas. Farmers were contacted via the Farming Cooperative of Region of Distrito Federal (COOPA/DF, abbreviation in Portuguese). Our region study is embedded by the Brazilian savanna (Cerrado), a hotspot of biodiversity that is under threat by landscape simplification (STRASSBURG et al., 2017). All the research procedures were conducted with the landowner’s permission.

Data collection was carried out in 35 sampling sites located in 11 fields belonging to seven farmers during two crop seasons (27 sampling sites in 2015/2016 and eight in 2016/2017 – November to January). Depending on the field size, we selected two to six sampling sites per field covering a gradient of distance to the natural habitat (i.e., from 18 to 1152m), maintaining a minimum distance of 300m between locations (Table 4 in Supplementary Material S2).

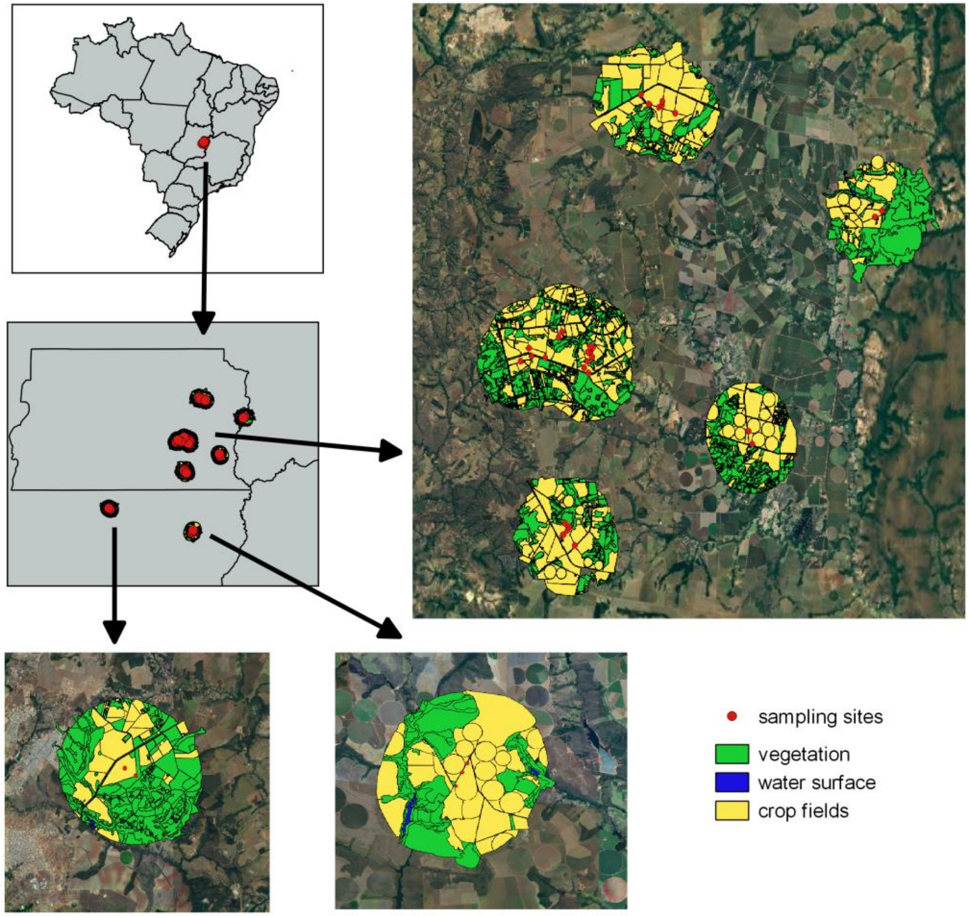

FIG. 10 – Study area located in the central region of Brazil, showing the location of the 35 sampling sites used in this study. This area is characterized by high degree of land conversion, with large monocultures. The image provides an example of buffers (3500 meters radii) with land-use classes selected around the sampled fields.

Source: Elaborated by authors.

2.2. Pollinator data collection

In each site, we collected information on pollinator density and diversity following the methodology proposed by Vaissière et al. (2011). First we count the number of flowers and pollinator (abundance) along two parallel transects (25x1m). Data collection occurred during morning (09h00 to 12h30) and afternoon (13h00 to 16h00), maintaining an interval of three hours between surveys (so each site was sampled twice within a single day of the peak of flowering). Afterwards, insects were captured along transects, and later identified by taxonomists to estimate the richness of pollinators (number of species). Information of uncollected morphospecies, which description did not match with collected species, was also considered in richness. As the number of flowers varied among plots, then, we calculated pollinator density and diversity by dividing the abundance and richness, respectively, by the total number of flowers. For further details on sampling design and pollinator density and diversity data collection, see appendix A and Ramos et al. (2018) in annex A.

2.3. Effect of pollination on crop yield and quality

To collect data on yield and crop quality for each sampling site, 15 individual plants were randomly gathered along two parallel transects (25x1m). After desiccation of the beans (collected ca. 90 days after planting), all pods produced by the selected plant were counted (including thin pods with no beans, due to lack of ovule fertilization). The number of seeds were counted and placed in a 65º C kiln until the humidity level was below 14%, a procedure that corresponds to commercial bean processing (BRAGANTINI, 2005). The beans were then weighed and selected for quality assessment.

The effect of pollinators on yield can be estimated based on the increase of the number of ovules fertilized per flower (i.e., weight per pod) with density and diversity of visits, as estimated by Ramos et al. (2018). The estimated effects of native pollinators (*A. mellifera*) were extracted from Ramos et al. (2018). All estimates were converted so that yield would be given in kg per hectare, a unit scale typically used by farmers. For conversion we used the average pod per square meter (i.e., 144 pod/m^2), which was calculated using the average number of flowers produced per plant (i.e., 30 flower/plant), the average percentage of flowers that became pods (i.e., 40%) (see MARTINS, 2017), and the average number of plants per square meter observed during crop season in our study region (i.e., 12 plants/m^2) (see RAMOS et al., 2018).

Common bean quality was assessed taking into account a method of classification used by market, which is based on size and color information. The information on how pollination services affect common bean quality was extracted from Chapter 1. Fifteen beans were randomly selected from each sampling site. The beans were grouped into two size classes separated by a length threshold of 10mm (following BRASIL, 2008 and 2009). To assess color, visual comparison method was applied to mimic what is used by farmers. To minimize subjectivity, we selected beans that covered a range of colors found in the study region and created a scale of tonalities varying from 1 (darker) to 3 (clearer) (see Fig. 2). This scale was used as a reference to classify each of the selected beans. Information on size and color were combined to classify beans of each sampling site in two quality classes used by farmers: High and Low quality. 'High quality' beans must be more than 10mm in length and have a color parameter of 3. All others beans were considered as low quality beans.

FIG. 11 – Tonality scale used for the common bean. The highest number (lightest tonality) is associated with higher market price.
Source: Elaborated by authors.

2.4. Brazilian Forest Code

The Brazilian policies for nature conservation consist in two institutional arrangements: i) Preservation Areas (public national and state conservation parks and Indian reservations), and ii) Forest Code that is framed in two target areas: i) Permanent Preservation Areas (PPA), and ii) Legal Reserve (LR) (FEDERAL LAW 12.727/2012). The supervision of farmers by the government will be via Rural Environmental Registry (RER, in Portuguese or CAR – *Cadastro Ambiental Rural*) that consists in a registry via geo-referenced information on Legal Reserve and Permanent Preserved Areas located in all Brazilian private properties.

Permanent Preservation Area (PPA – *Área de Preservação Permanente* “APP”) aims to preserve biodiversity, water resource, soil around sensitive areas, and to facilitate the genetic flow of wild life. The PPA is a cover of natural vegetation that includes riparian areas along all type of water surface (e.g., riversides), slope areas >45º, high altitude areas >1.800m, mangrove areas, *restinga* areas, board of plateau, and hilltops of mountains higher than 100m (see Fig. 12).

Legal Reserve (LR – *Reserva Legal* “RL”) is a cover of native vegetation located inside the private owned land to protect biodiversity and to shelter the wild life. In properties located in Legal Amazon Region (LAR) the percentage is 80% in forest areas, 35% in area of savanna, and 20% in grassland area, and for properties located outside of LAR the percentage is 20%. This target area can be managed with low-impact production systems, but the complete forest removal is not allowed.

Comparing to Legal Reserve, PPA is more acceptable by farmers because these areas aim to conserve water resources, to reduce soil erosion and sediment flows in rivers (SPAROVEK et al., 2012). However, Legal Reserve is usually the main source of tensions between farmers and authorities because, depending on its size, the economic feasibility of crop system can be affected.

Landscape 1 | Landscape 2 | Landscape 3

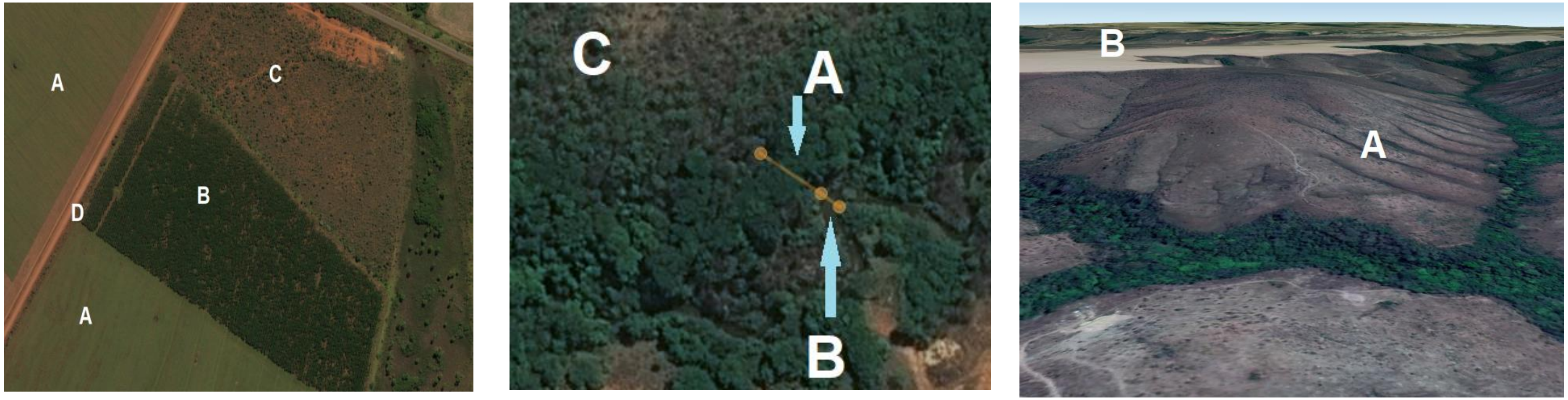

FIG. 12 – Potential areas for Legal Reserve and Permanente Preserved Areas. Landscape 1 (15º42'26.1"S 47º26'40.8"W): 'A' and 'B' fields of temporal and permanent crops, respectively; 'C' – potential area for Legal Reserve; 'D' – edge of rural streets. Landscape 2 (16º08'54.5"S 47º53'22.5"W): 'A' – Potential area for Permanent Preserved Area (riparian area of 30m); 'B' – water body of 10m of width; 'C' – potential area for Legal Reserve. Landscape 3 (15º57'06.0"S 47º37'23.1"W): 'A' and 'B' – Potential area for Permanent Preserved Areas (slope areas, board of mountains and board of plateau).

Source: Elaborated by authors.

2.4.1. Landscape data collection

To apply the institutional arrangement of Forest Code in our study region, we used a landscape approach to identify potential areas that could be considered as Permanent Preserved Areas and Legal Reserve. We classified landscape in four classes, taking into account classifications used by the environmental laws in Brazil: Permanent Preserved Area (PPA), Legal Reserve (LR), cropland, and others occupations (Fig. 13 and Table 5 in Supplementary Material S2).

In our sampled landscape, we found PPA of riparian areas of 30m that are associated to water surface with width below of 10m and in only one location we found PPA of riparian area of 200m associated to water surface with width between 200 and 600m. Water surface was identified using watershed data from State System of Geoinformation (SIEG – *Sistema Estadual de Geoinformação* in Portuguese, 2018). The potential areas for Legal Reserve (LR) were identified as any area of natural vegetation which was not classified as PPA. For cropland, we considered fields dedicated to temporary and permanent crops (see Fig. 12 – Landscape 1). Lastly, other occupations category refers to remaining areas that include built-up areas, water body, road and streets, cloud and cloud shadow, areas of disturbed vegetation that could not be classified as PPA and LR (e.g., board of streets, gardens, and hedgerows).

Using Quantum GIS 2.18.2 (QGIS Development Team, 2018), landscape data were gathered from a circular area with 2 km of radius to represent the potential foraging activity of pollinators in each sampling site. Digitalization was performed tracing the boundaries between target areas, cropland, and other occupations visible in 2016 aerial imagery from Google Earth using the OpenLayer Plugin. All landscape calculations were repeated for four different spatial scales (radius of 0.5km, 1km, 1.5km, and 2km) (Fig. 13).

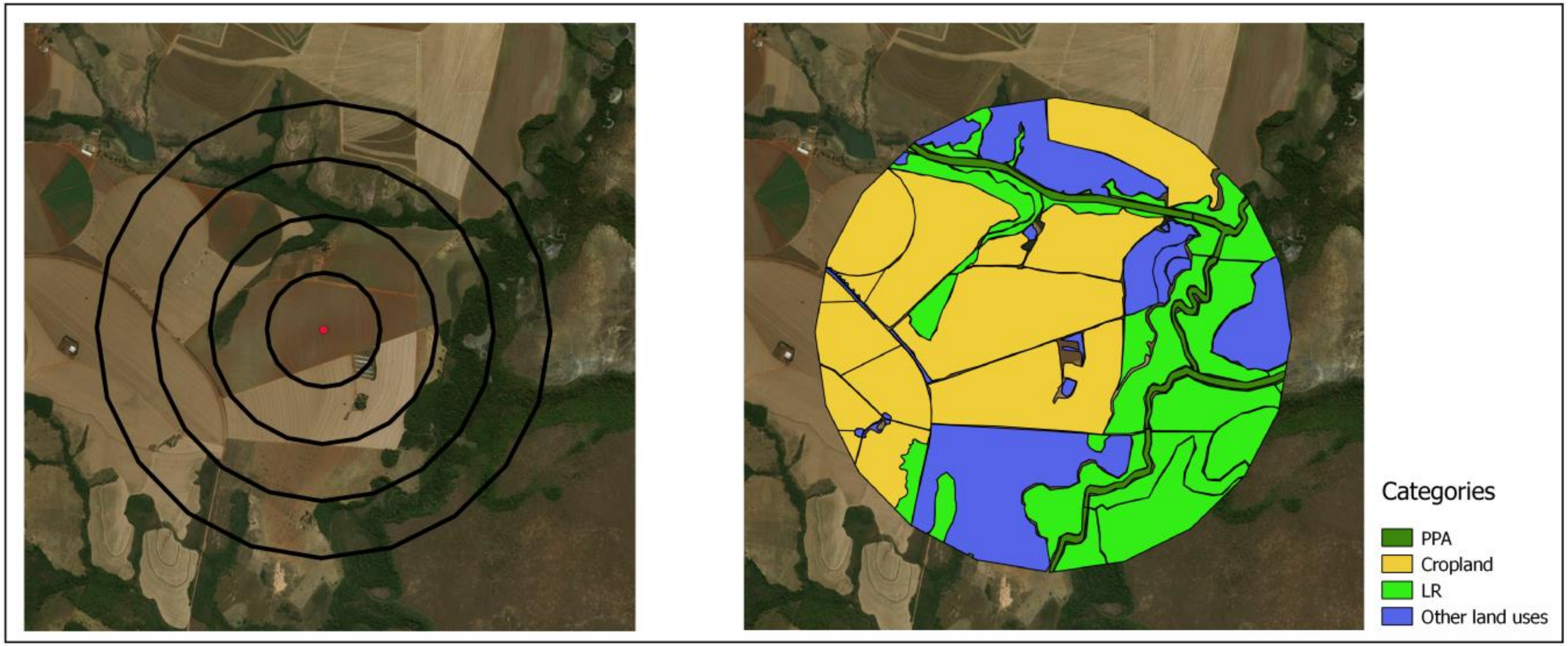

FIG. 13 – Spatial scale and landscape classification of rural area in Distrito Federal/Brazil. Circular areas represent the four spatial scales assessed in our study. Red point indicates one sampling sites (15°46'09.6"S 47°20'18.4"W). ‘PPA’ is potential areas for Permanent Preserved Areas and ‘RL’ indicates potential areas for Legal Reserve.

Source: Elaborated by authors.

2.5. Statistical analysis

To select the appropriate landscape scale for pollinator management via target areas, we used a Generalized Linear Mixed Model (GLMM) assuming negative binominal distribution to assess the effect of the total percentage of target areas (i.e., potential areas for PPA and LR) at each of the four landscape scale (0.5-2km radius) on pollinator variables (i.e., abundance of native pollinators and diversity). The GLMM was an appropriated statistical approach because it can deal with the problem of pseudo-replication (i.e., one field with two or more sampling site) that is inherent in our data set (BOLKER et al., 2008). To account for the temporally nested sampling design, 'year' was included as a random variable. As some participating farmers owned more than one field, in which strategies for cropland management may differ between farmers (e.g., sowing data and fertilizer management), we also included crop 'field' within 'farmers' in the random structure of the model. The selection of most appropriate landscape scale was based on Akaike's Information Criterion, corrected for small sample size (AICc).

After selecting the most appropriate spatial scale, we assessed how pollination variables (i.e., abundance and richness of pollinators) were influenced by Permanent Preserved Area and Legal Reserve (objective 1). GLMM, negative binominal distribution, and the same random structure used in landscape scale analysis were applied here (i.e., 'year' and 'field/producer'). We then applied a model selection procedure based on Akaike's Information Criterion, corrected for small sample sizes (AICc). In cases where two or more models had similar predictive power (i.e., ΔAIC < 2, considering the best model AICc as a reference), the averaged model was calculated. Averaged estimators reduce bias and have higher precision (BURNHAM and ANDERSON, 2002).

All statistical analyses were carried out with R (R Development Core Team, 2017), using the 'lme4 version 1.1-12' package for GLMM (BATES et al., 2015) and the 'MuMIn' package for model selection ('dredge' function) and averaging model ('model.avg' function) (BARTON, 2015).

2.6. Economic assessment

Using the framework for economic assessment of crop pollination developed in Chapter 1, we analyzed how landscape management of PPA and LR affects farmers' profitability via pollination services (objective 2). More specifically we considered variations in profitability associated to increasing percentage of Legal Reserve and Permanent Preserved Areas at landscape level. The applied framework integrates the effect of two practices of pollinator managements (i.e., natural pollinator management and honeybee management) and the conventional practices (e.g., pesticides, fertilizer, among others) on crop yield and quality to estimate crop profitability (USD/ha). The information on the effect of LR and PPA on native pollinator abundance and diversity were integrated via pollinator natural capital component. The effect of managed bee was considered as null because none significant variation on profit was detected comparing scenarios with and without honey bee hives application. For fertilizer use, we considered the recommended dosage of nitrogen application for common bean in our study region (i.e., 60 $kg.ha^{-1}$, see SOUSA and LOBATO, 2004). Native pollinator abundance was converted in density using the average number of flowers observed along transects (i.e., 1945 flowers). As the number of flowers varied across fields, diversity was also divided by the average number of flowers to standardize the sampling effort. The effect of native pollinator density and diversity on common bean yield was extracted from Ramos et al. (2018) and the effect on common bean quality was extracted from Chapter 1, as well as the information on production cost and market prices associated to each crop quality category of this crop. All equations to run this framework are presented in Table 3 in Supplementary Material S2 (an expanded version of the adapted framework is in Supplementary Material S3).

2.6.1. Economic compensation

In the case when LR is below of percentage defined by the Forest Code, farmers must reforest the LR by their own cost, to set aside an area to regenerate the natural vegetation, to rent the land on environmental easement, or to purchase

Environmental Reserve Quotas (ERQ or CRA – *Cota de Reserva Ambiental* in Portuguese). The ERQ consist in a certificate to landowners of one hectare of native vegetation preserved above of the minimum percentage required for Legal Reserve, within the property, including areas reforested with native species at any stage of regeneration. The ERQ market consists in a trade of certificates between farmers that conserve more than the minimum percentage required for Legal Reserve (LR-surplus) and farmers with LR-deficit, so that the later would cope with legislation. ERQ price is based on the municipality land prices that is resulted from the agricultural economic returns, regional transaction costs (i.e., expenditure to legalize the certificates), and the cost of fencing needed to isolate the ERQ area (SOARES-FILHO et al., 2016). The average ERQ price in the biome of our study region (i.e., Brazilian savanna – *Cerrado*) was estimated in 1047 USD/ha by Soares-Filho and co-authors (2016) for values in 2030. We used the average of the interest rate during 2015 and 2016 (period of research field) (i.e., 6.88%) of the Brazilian Constitutional Found of Financing of Midwest Region (Fundo Constitucional de Financiamento do Centro-Oeste – FCO Rural), a financial program to support the rural production, as a discount rate to estimate current value at 2015 (i.e., 385.92 USD/ERQ). Although this certificate is not directly associated to pollination services because the trade can be made between farmers located inside the same biome (i.e., far away from the productive farmland), it is a voluntary transaction (i.e., exist other options to compensate LR) between two farmers to pay for ecosystem services that emerge from a well-defined land use (see WUNDER, 2005). Thus, ERQ is a great instrument to simulate the internalization of such externalities and the Brazilian Forest Code is an interesting institutional arrangement to test the effect of an environmental policy on farmers' profit, taking into account the benefit with pollination services and economic compensation.

The variability in total profit of farmers considering the enhanced profitability and economic compensation of positive externalities (objective 3), will be estimated in a hypothetical farmland in which area fits with the more appropriated spatial scale for pollinator management (see results). In this simulation, we considered that the same percentages of Legal Reserve and Permanent Preserved Areas occur at landscape and within the hypothetical farmland. Thus, increasing conserved areas will result in the reduction of cropland in the same magnitude. Total profit was estimated multiplying the profitability and available cropland after its reduction with conserved areas. In addition, for scenarios of Legal Reserve percentage below the required percentage in our study region (i.e., 20%), farmers must purchase ERQ to compensate LR-deficit whereas for farmers with LR-surplus they will be rewarded by selling the ERQ, considered here as the internalization of externalities (Eq. 1).

$$profit = \begin{cases} profitability * cropland - ERQ_{LRdeficit} * price, \ LR < 20\% \\ profitability * cropland + ERQ_{LRsurplus} * price, \ LR > 20\% \end{cases} \quad (1)$$

3. Results

3.1. Effect of LR and PPA on pollinator agents

The appropriate spatial scale for landscape management taking into account potential areas for Legal Reserve and Permanente Preserved Areas was 0.5km radius for both native pollinator density and diversity (Table 7 in S2). The percentage of potential areas for Legal Reserve (LR) varied greatly across landscape from 0 to 60% whereas the Permanent Preserved Areas (PPA) presented a maximum percentage at 3% (see Table 4 in S2). Taking into account the low variability of PPA in our sampled landscape, our economic estimates were done considering the average percentage of such area (i.e., 1.5%).

Both native pollinator abundance and diversity were influenced by landscape management via Legal Reserve and Permanent Preserved Areas (objective 1). Native pollinator abundance was positively associated to potential areas for Legal Reserve whereas both target areas increased pollinator diversity on common bean fields, being these last effects less accentuated than that one on native pollinator abundance (Fig. 14 and Table 8 in S2). The majority of sampling sites was located at landscape with Legal Reserve below the required percentage for our study region (i.e., 20%) (see ‘gray dots’ in Fig. 14).

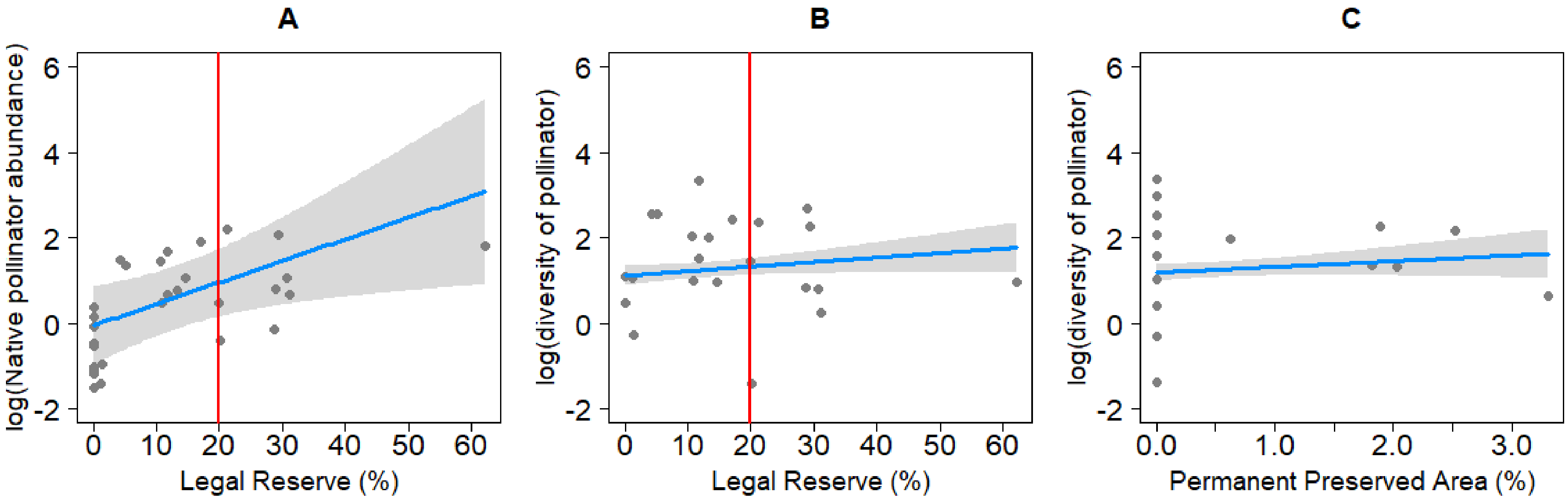

FIG. 14 – Effect of potential areas of Legal Reserve (LR) and Permanent Preserved Area (PPA) on pollinator agents. This result was based on the percentage of PPA and LR at 0.5km of spatial scale. “A” depicts best model for native pollinator abundance and “B” and “C” depict model 1 and 3 for diversity, respectively (see Table 8 in S2). Abundance was the number of visitors observed in flowers and diversity was the number of species of collected and observed visitors. ‘Red line’ indicates the minimum percentage required for Legal Reserve in our study region (i.e., 20%) and ‘gray dots’ indicate observations. Shaded area represents 95% confidence interval.

Source: Elaborated by authors.

3.2. Farmers’ profitability and pollination services mediated by conserved areas

Increased profitability (USD/ha) by pollination services depends on how pollinator agents contribute to crop yield and quality. Ramos et al. (2018) showed that common bean yield was positively associated with native pollinator density, but only under low levels of fertilizer input. In Chapter 1, we showed that, under a high diversity of pollinator species and nitrogen application, density of native pollinators increase the probability of a given seed of being classified as high quality. Here, we estimate profit variation taking into account pollination services of native pollinator mediated by conserved areas of Legal Reserve and Permanente Preserved Areas.

Variation in the percentage of both target areas at 0.5km of spatial scale influenced farmers’ profitability (USD/ha) in common bean production via pollination services (objective 2) (Fig. 15). Estimated profitability (USD/ha) due to pollination services varied between 96.20 up to 763.02 USD/ha considering a landscape context of zero and 80% of Legal Reserve and Permanent Preserved Areas, respectively (for calculation report see Supplementary Material S3). Farmers in our study region must to conserve 20% of Legal Reserve, at this level of vegetation cover; profitability was estimated in 160.93 USD/ha. Thus, increasing the percentage of Legal Reserve has a potential to be considered as a profitable strategy for farmers.

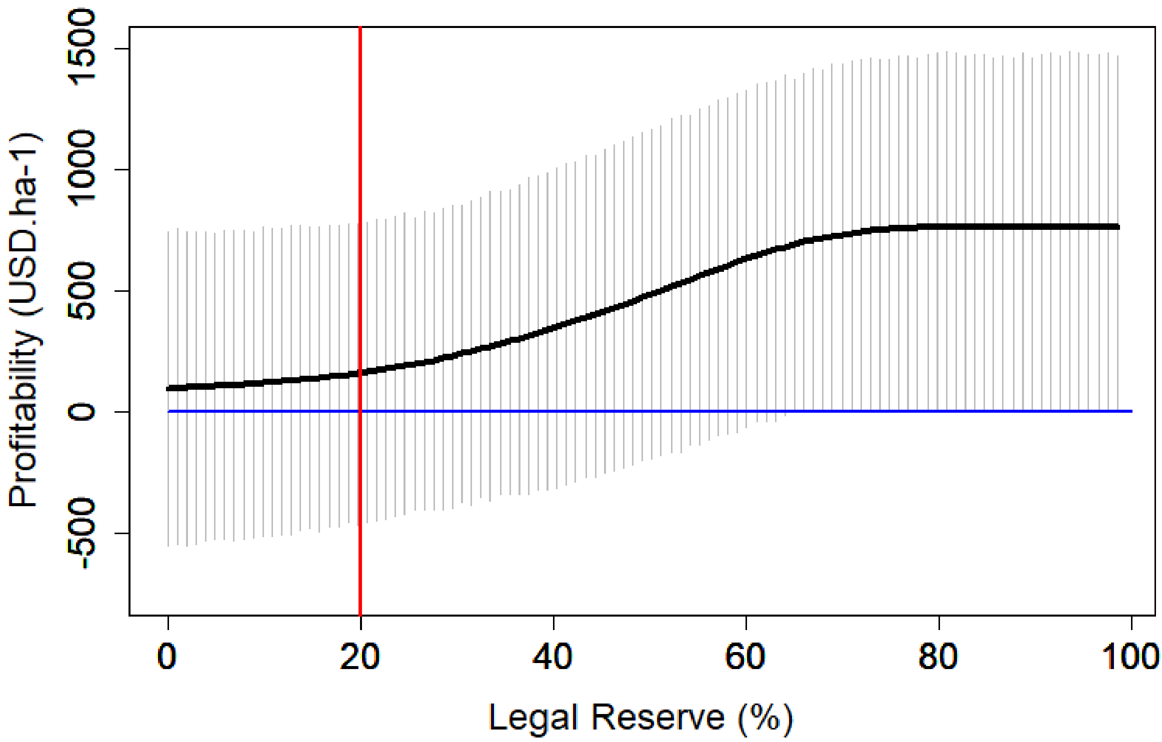

FIG. 15 – Effect of overall cover of areas that fit Legal Reserve (LR) description on the profitability of 1ha of land. This result was based on the percentage of LR and PPA at 0.5km of spatial scale. Profitability was estimated with average percentage of PPA (i.e., 1.5%). 'Red line' indicates the minimum percentage of Legal Reserve that farmers are enforced to maintain within their properties in our study region (i.e., 20%). Shaded area represents 95% confidence interval and 'blue line' indicates zero value for profitability.

Source: Elaborated by authors.

3.3. Farmers' profit, pollination services and internalization of externalities

Using information on profitability (USD/ha), we assessed how conserving target areas and associated economic compensation may bring economic benefit for farmers (objective 3). Taking into account a hypothetical farmland area of 78ha (i.e., total area in a circular area of 0.5km radius), we calculated total profit (USD) in the available cropland after the reduction due the expansion in Legal Reserve, considering 1.5% of Permanente Preserved Areas. In a scenario with no economic compensation, total profit presented a positive trend by increasing from 7503.62 USD up to 18985.49 USD at 60% of Legal Reserve ("No compensation" - Fig. 16). Afterwards, this trend became negative because the restriction in cropland areas presented a more accentuated effect on the crop production.

Taking into account the internalization of externalities via Environmental Reserve Quotes (ERQ), we estimated two situation for total profit considering the product between ERQ (USD/ha) and the current area for Legal Reserve (ha): i) ERQ as a cost in farmland with less than 20% of Legal Reserve (LR); and ii) ERQ as additional revenue for that with more than 20% of LR ("With compensation" - Fig. 16). In the first case, as expected, decreased profit by ERQ cost was less than profit mediated only by pollination services (i.e., "green line" – Fig. 16). For the second situation, ERQ, as additional revenue, increased profit for farmland areas that have Legal Reserve up to 70%. In addition, profit mediated by pollination services (green line) represented the majority of total profit.

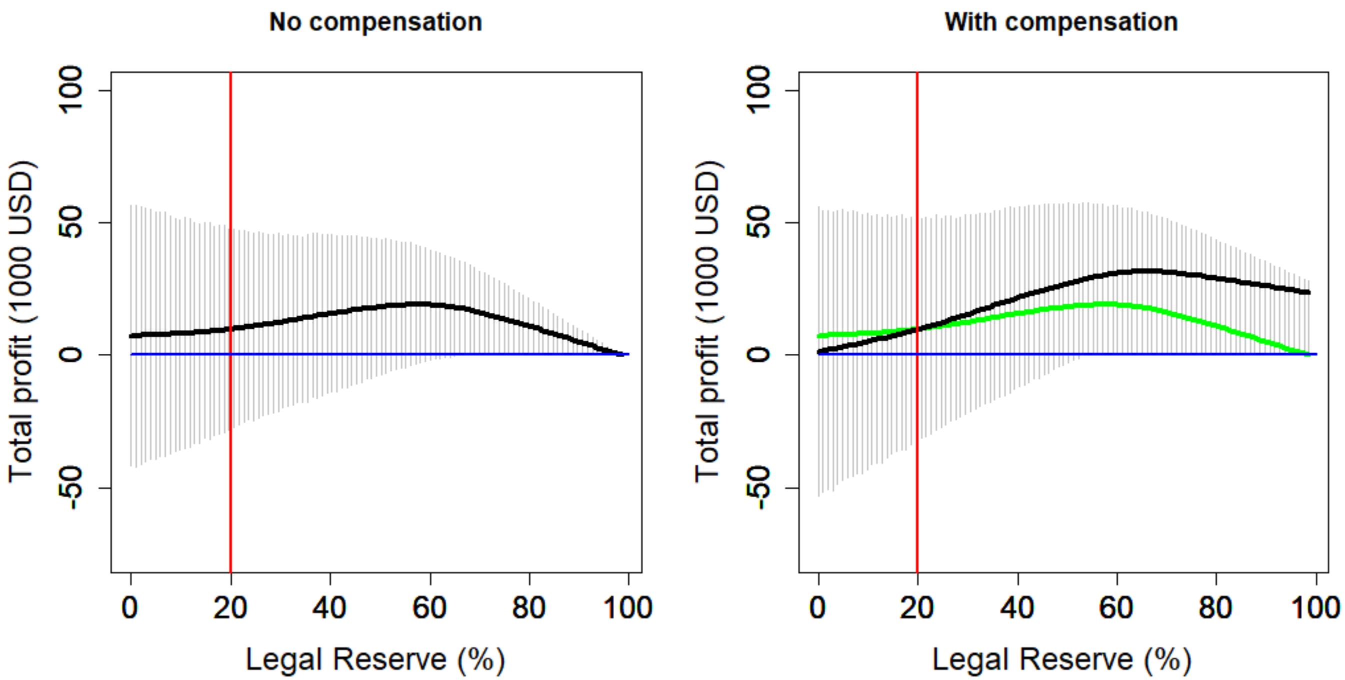

FIG. 16 – The effect of landscape management and economic compensation of externalities on total profit. This result was based on the percentage of PPA and LR at 0.5km of spatial scale, in which we assumed that fit a farmland area of 78ha. Total profit was calculated multiplying profitability by available cropland after the restriction with LR expansion indicated in x-axis and 1.5% of PPA. 'Red line' indicates the minimum percentage of Legal Reserve (i.e., 20%) that farmers must to conserved inside their properties in our study region. 'No compensation' scenario only considers the effect of pollination services on profit whereas 'with compensation' scenario also includes an economic compensation of externalities calculated by the multiplication between average price of Environmental Reserve Quotes (i.e., 385.92 USD/ERQ) and LR-deficit for LR <20%, representing an additional cost, or LR-surplus for LR >20%, representing an additional revenue (see Eq. 1). Shaded area represents 95% confidence interval and 'blue line' indicates zero value for total profit. 'Green line' indicates total profit shaped by pollination services in the scenario with no compensation (see Supplementary Material S3).

Source: Elaborated by authors.

4. Discussion

Nature conservation inside private owned lands is a great challenge for environmental policies because not all farmers are willing to participate. Here, we demonstrate in which circumstances current environmental policies can bring economic benefits to farmers considering crop pollination and internalization of externalities. Using the Brazilian environmental law as an institutional context, potential areas for Legal Reserve (e.g., minimum percentage of nature vegetation) and Permanent Preserved Areas (e.g., riparian areas of small rivers) are important habitats to conserve pollinators and their pollination services. Such service enhances farmers' profitability in common bean production, via crop yield and quality, even with no economic compensation.

The broad variation in profitability and profit can be expected in a context with extremely supply of pollination services, which can be difficult to achieve in real world conditions. Pollination services positively affected profitability (USD/ha) and profit (USD) in farmland areas with Legal Reserve up to 80% and 60%, respectively. Farmland areas with 60-80% (or more) of vegetation cover also offer a great number of pest agents, which would be considered as a threat by farmers, so motivating then to apply more pesticides or converting more vegetation cover into cropland. In addition, farmers commonly consider that areas close to natural habitat present more pest agents that those more isolated (farmers' personal communication). Such percentage of Legal Reserve is difficult to find in real situation because our study region has been extremely affected by agribusiness expansion (STRASSBURG et al., 2017). Lastly, farmers that own farmland areas with few vegetation areas (e.g., 10% of Legal Reserve) intensify their management by using more chemical inputs, increasing the plant density in crop field, and/or applying others technologies (e.g., modified seeds) in order to ensure higher productivity. As common bean is a crop with some level of self-pollination, those conventional practices may bring higher profitability than that estimated in a scenario with no pollination services mediated by conserved areas (i.e., 96 USD/ha).

Our estimated also presented uncertainties associated to profit projection (Shaded areas in Fig. 16 and 16). The projection of profit was done by combining all models considering in this study (i.e., effect of LR and PPA on pollinator agents), in Chapter 1 (i.e., effect of pollinator on common bean quality), and in Ramos et al. (2018) (i.e., effect of pollinators on common bean yield). Such aggregation was done via the sum of effect of all parameters and its associated errors presented in that models integrated in the framework. As a result, a part of the projected uncertainty associated to profit estimation was below of zero, thus, indicating a probability of existence of financial loss. The probability of loss presented in the profitability and profit estimates was associated to farmland areas with less than 70% of Legal Reserve. Although we recognize such uncertainties, our results demonstrated a clear trend in profitability and total profit that corroborate the assumption that crop pollination mediated by conserved areas increase farmers' economic output.

Internalization of externalities is an important way to motivate farmers to conserve natural areas within their rural property. For landowner that has less than required percentage of Legal Reserve, the impact of the cost associated to environmental compensation (i.e., payments for those that are conserving in their properties) is dependent on vegetation cover within rural property and the certificate price, in our case was ERQ (USD/ha). The first is controlled by farmers, but ERQ price is defined at market by the interaction between suppliers and buyers of such certificate. Thus, in the context with ERQ scarcity, the market prince will increase and affect the cost of compensation. For example, Soares-Filho et al. (2016) estimated that ERQ price could vary between 400-15000 USD/ha, being our study region one of the areas with the highest price for this certificate. Others regions with expensive ERA price projection are South and Southeast of Brazil, being North and Northeast the less expensive. Thus, for farmers located at those areas, reforestation of Legal Reserve, not only for complying environmental law, but also to gain economic payments for conservation can be a great opportunity. However, such environmental policy has some frailties that will be discussed below.

4.1. Limitations

The sampled landscape included some types of Permanent Preserved Areas and Legal Reserve. In our analysis, Permanent Preserved Areas varied between zero and 3%, including several riparian areas of 30m and one of 200m. The Brazilian Forest Code defines a variety of areas that can be considered as PPA, such as slope areas, edge of mountains, hilltops, among others, that can host a number of crop pollinators (see Fig. 12 and Table 8 in S2). Thus, a more broad sampling effort is needed to gather a great quantity and diversity information on PPA to understanding its role in crop pollination provision. For Legal Reserve, our study was limited in natural areas of Brazilian savanna (*Cerrado*), but it is also important to understand the role of Legal Reserve as a crop pollination provider in other biomes. Although our results are restricted to the study of case, it indicates that Legal Reserve and PPA do influence pollinators on crop fields and how conservation strategies can be economically evaluated in order to support farmers' decision-making process. Thus, future studies are needed to assess the importance of a gradient of PPA and LR and whether both target areas are mutually influenced by each other in the provision of crop pollination.

4.2. Frailties in market-based instruments of environmental policies

National level policies that aim to improve citizens' wellbeing and national economy also rarely integrate spatial targeting areas for conservation of nature (BATEMAN et al., 2013), including areas within rural private properties that may be potential provider of pollination services. Although target areas, such as Legal Reserve and Permanent Preserver Areas, aim to provide a range of ecosystem services that economically benefit farmers, environmental policies present some frailties associated to internalization of externalities. Although Permanent Preserved Areas tend to be more acceptable by farmers if compared to Legal Reserve (SPAROVEK et al., 2012), this last is an important source of new revenues associated to ecosystem services and the trade of ERQ. Internalization of positive externalities, such as via ERQ, could encourage farmers to increase their economic benefit by expanding conserved areas. However, farmers' behavior is difficult to predict only considering the potential economic gain with pollination services and internalization of positive externalities.

For the conservation of those target areas, restricted cropland can engender conflicts between farmers and government, then reducing the effectiveness in environmental policy. Although market incentives is one of the main motivations for changing farmers' behavior, other instruments could also be effective in stimulating the adoption of conservation actions by farmers, such as public contracts, social moral, and "command and control" legislation (WILLIAMSON, 2000; SNOO et al., 2013). Thus, the effectiveness of market-based instruments is also influenced by the institutional and social context.

Economic compensation is a broad solution that includes payment for ecosystem services, certification of crops produced under pollinator-friendly practices (OLSCHEWSKI al., 2006), Agri-environment Scheme (e.g., in Europe), and Environmental Reserve Quotas (e.g., in Brazil). Such environmental programs are applied at different institutional levels, for instance, Programs for Payment of Environmental Service were established by both national level, e.g., Costa Rica, and local level, e.g., the Brazilian county of *Silvânia*, state of *Goiás* (SILVÂNIA, 2018). Such instruments are dependent on the flow of financial resources, because if the payment flow is ceased the action for conservation may also be interrupted. Farmers also may be not interested in the payment, especially when it is surpassed by the expected gains with farming activities. Finally, such approaches are more difficult to implement by government in countries with limited budged for conservation programs, especially in developing nations. For such countries, an involuntary approach can be more effective, for example, the case of Legal Reserve and Permanent Preserved Areas in Brazil. However, such command-control regulations present an elevated cost for supervision of farmers, for example, monitoring technologies, training public agents, transition cost, among others. In addition, such approach cannot compromise the economic feasibility in crop system neither the production of self-consumption by restricting cropland. A flexible combination between voluntary and involuntary approaches can be adapted in several contexts, increasing the effectiveness of environmental policies. Finally, it is expected that environmental policies create the conservation mind in farmers, but changing mindset is not a trivial task because also require a long term strategy in environmental education (SNOO et al., 2013)

Other frailty associated to economic mechanism of compensation is that landowner can purchase certificates of natural vegetation in areas less appropriate for agricultural production. Since ERQ price follows the price of land, which is resulted from economic return of farming activities (SOARES-FILHO et al., 2016), this may result in regions extremely converted in cropland and in conserved areas in less suitable lands for agriculture, a phenomenon called leakage (i.e., displacing environmental impact elsewhere) (ENGEL et al. 2008; SIMPSON, 2014). Thus, as benefits received from pollination services depend on the proximity between crop field and natural habitat, profit shaped by such services in addition with economic compensation is a way to motivate farmers to protect natural vegetation inside their own rural property.

5. Conclusion

Nature conservation inside private owned land has a great potential to protect biodiversity and its associated ecosystem services (e.g., crop pollination, bio-control agents, among others) with potential benefit for crop production and farmers' economic output. Environmental policies that aim to stimulate conservation practices by farmers have to inform them on how they would be benefited via ecosystem services and in which circumstance they would receive (or pay) an economic compensation. Farmers that apply biodiversity-friendly practices became a provider of ecosystem services to other farmers that, in turn, benefit the society (positive externalities). Recognizing the role of farms not only as a producer of agricultural products but also as a provider of ecosystem services by government and society would stimulate a general coordination of nature protection inside private-owned land.

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Supplementary Material S2

Table 4 – Landscape information in all sampling sites. 'LR 0.5' indicates the percentage of Legal Reserve at and 'PPA 0.5' the percentage of Permanent Preserved Areas both at a spatial scale of 0.5km.

year	field	farmer	Sampling sites	Latitude	Longitude	LR 0.5	LR 1	LR 1.5	LR 2	PPA 0.5	PPA 1	PPA 1.5	PPA 2
2015	1	A	1A	-16.124894	-47.877333	0.60	0.44	0.36	0.31	0.02	0.07	0.05	0.04
2015	1	A	1B	-16.121561	-47.882889	0.00	0.27	0.23	0.24	0.00	0.00	0.02	0.03
2015	2	B	2A	-15.918783	-47.411775	0.15	0.09	0.12	0.18	0.03	0.02	0.02	0.01
2015	2	B	2B	-15.909617	-47.435386	0.00	0.00	0.02	0.06	0.00	0.00	0.00	0.01
2015	3	B	3A	-16.217118	-47.546220	0.12	0.18	0.17	0.17	0.00	0.00	0.00	0.01
2015	3	B	3B	-16.211006	-47.543720	0.00	0.03	0.14	0.17	0.00	0.00	0.00	0.00
2015	3	B	3C	-16.207117	-47.541498	0.00	0.01	0.10	0.18	0.00	0.00	0.00	0.00
2015	4	C	4A	-15.864060	-47.609831	0.01	0.08	0.12	0.20	0.00	0.02	0.02	0.02
2015	4	C	4B	-15.860727	-47.601498	0.04	0.09	0.14	0.15	0.00	0.00	0.01	0.01
2015	5	D	5A	-15.855172	-47.554553	0.11	0.06	0.22	0.18	0.00	0.00	0.02	0.02
2015	5	D	5B	-15.854061	-47.556498	0.11	0.10	0.23	0.18	0.00	0.01	0.03	0.02
2015	5	D	5C	-15.858783	-47.556498	0.01	0.16	0.22	0.21	0.00	0.01	0.01	0.02
2015	5	D	5D	-15.857949	-47.558164	0.01	0.18	0.23	0.21	0.00	0.00	0.01	0.02
2015	6	D	6A	-15.871561	-47.557886	0.29	0.44	0.38	0.36	0.00	0.00	0.00	0.01
2015	5	D	5E	-15.864338	-47.558442	0.29	0.22	0.27	0.26	0.00	0.01	0.00	0.01
2015	5	D	5F	-15.861283	-47.555109	0.15	0.20	0.21	0.12	0.00	0.01	0.01	0.00
2015	6	D	6B	-15.868227	-47.561220	0.20	0.35	0.32	0.18	0.00	0.00	0.00	0.00
2015	7	E	7A	-15.972117	-47.572609	0.05	0.08	0.11	0.10	0.00	0.00	0.02	0.02
2015	7	E	7B	-15.969894	-47.575942	0.12	0.15	0.13	0.12	0.00	0.02	0.02	0.02
2015	7	E	7C	-15.974617	-47.573998	0.00	0.05	0.07	0.08	0.00	0.00	0.01	0.02
2015	7	E	7D	-15.977394	-47.577331	0.00	0.02	0.03	0.07	0.00	0.00	0.00	0.01
2015	7	E	7E	-15.984339	-47.568442	0.00	0.01	0.04	0.07	0.00	0.00	0.00	0.01
2015	8	F	8A	-15.695727	-47.511219	0.19	0.23	0.24	0.25	0.02	0.01	0.01	0.01
2015	8	F	8B	-15.697671	-47.503997	0.00	0.09	0.11	0.17	0.00	0.00	0.01	0.01
2015	8	F	8C	-15.696282	-47.501497	0.00	0.02	0.07	0.11	0.00	0.00	0.00	0.00
2015	9	G	9A	-15.765449	-47.332885	0.13	0.27	0.27	0.30	0.01	0.06	0.04	0.04
2015	9	G	9B	-15.769338	-47.338440	0.00	0.12	0.23	0.28	0.00	0.00	0.04	0.03

2016	8	F	8D	-15.689338	-47.517886	0.31	0.22	0.23	0.27	0.00	0.00	0.01	0.00
2016	8	F	8E	-15.693782	-47.501219	0.00	0.00	0.05	0.07	0.00	0.00	0.00	0.00
2016	8	F	8F	-15.695449	-47.511775	0.18	0.23	0.25	0.26	0.02	0.01	0.01	0.01
2016	8	F	8G	-15.701560	-47.491497	0.00	0.00	0.08	0.14	0.00	0.00	0.00	0.00
2016	9	C	9A	-15.848410	-47.580789	0.27	0.32	0.21	0.17	0.03	0.02	0.01	0.01
2016	9	C	9B	-15.844894	-47.578164	0.00	0.26	0.21	0.18	0.00	0.02	0.02	0.02
2016	10	C	10A	-15.861561	-47.591220	0.29	0.19	0.19	0.17	0.00	0.00	0.02	0.02
2016	10	C	10B	-15.855449	-47.603442	0.00	0.08	0.12	0.14	0.00	0.00	0.00	0.01
	Average percentage					**0.104**	**0.149**	**0.175**	**0.181**	**0.003**	**0.008**	**0.013**	**0.014**

Source: Elaborated by authors.

Table 5 – Criterion for the classification of Permanente Preserved Areas (PPA), Legal Reserve (LR), and other land use.

Target Areas	Description	Category	Definition	Found in sampled landscapes
Permanent Preserved Areas	Permanent Preservation Area (PPA) is defined to preserve the biodiversity, water resource and soil around sensitive areas whereas it facilitates the genetic flow of wild life. The landscape context of our research field only presented riparian areas.	water body width <10m	buffer area 30m	YES
		water body width between 10 and 20m	buffer area 50m	NO
		water body width between 50 and 200m	buffer area 100m	NO
		water body width between 200 and 600m	buffer area 200m	YES
		water body width >600m	buffer area 500m	NO
		Slope areas	>45º	NO
		edge of mountains		NO
		high altitude areas	>1.8km	NO
		mangrove		NO
		hilltops		NO
Legal Reserve	Legal Reserve (LR) is a cover of native vegetation located inside the private owned land to protect biodiversity and to shelter the wild life.	forest areas in Legal Amazon Region (LAR)	80%	NO
		savanna areas in LAR	35%	NO
		grassland areas in LAR	20%	NO
		areas outside LAR	20%	YES
Cropland	Areas of temporal and permanent crops.	Crops	Crop fields	YES
Other occupations	Others occupations category are remaining areas that include built-up areas, water body, road and streets, cloud and cloud shadow, small vegetation that could not be allocated at PPA and LR (e.g., board of streets, gardens, hedgerows), among others.	other ocuppations	other ocuppations	YES

Source: Elaborated by authors.

Table 6 – Equations used for the application of the proposed framework in Chapter 1. 'PPA' and 'LR' indicate the percentage of Permanent Preserved Areas and Legal Reserve in a spatial scale of 0.5km, respectively. Ramos et al. (2018) applied the transformation log(Y/(2-Y)) on yield to represent a sigmoid function (s-shape). The effect of managed bees (MB) was considered as null and the nitrogen input (N) was standardized in 60 kg.ha-1. Prices (USD.kg-1) were: 0.64 for high quality (HQ), and 0.54 for low quality (LQ). The average number of 144 flowers per m^2 was used to convert estimated yield (Ŷ) in kg.ha-1 and to convert abundance in density we used the average number of flower observed in transects during the peak of blooming in our study region (i.e., 1945).

Input	Equations	Source
Native pollinator abundance	$e^{(-0.055+5.05*LR)}$	
Diversity of pollinator	$e^{(1.18+13.32*PPA+1.05*LR)}$	
Yield Model Ŷ=[2/(1/exp(Y)+1] (g.flower^{-1})	-1.32+0.016*N-45.1*MB+(638.5-6.8*N)*NC1	Ramos et al. (2018)
High quality (HQ)	-1.77-0.00036*N-11.74*NC2+(3088-30.39*N-25330*NC2)*NC1	Chapter 1
Low quality (LQ)	1 – HQ	Chapter 1
Revenue (R) (USD.ha^{-1})	(0.64*HQ+ 0.54*LQ)*((Ŷ*144*10000)/1000)	Chapter 1
Production Cost PC) (USD.ha^{-1})	64.66+0.45*2.5*N+10900*MB+0.24*((Ŷ*144*10000)/1000)	Chapter 1
Profit (PF) (USD.ha^{-1})	R - PC	Chapter 1

Source: Elaborated by authors.

Table 7 - Selection of spatial scale in which pollinators respond to landscape management. Selection was based on Akaike's Information Criterion corrected for small sample sizes (AICc). Spatial scale selected was marked in bold for each pollinator variable and was used in subsequent data analyses.

Landscape scale (km)	Native pollinator abundance	Diversity
0.5	**147.5**	**144.0**
1	154.0	149.4
1.5	165.0	152.6
2	155.6	152.5

Source: Elaborated by authors.

Table 8 – The effect of potential areas for Permanent Preserved Areas (PPA) and Legal Reserve (LR) on abundance of native pollinators and diversity. 'PPA' and 'LR' areas were measured as the percentage within of landscape scale of 500m. 'X' indicates terms that were included in the models. All models were run with negative binomial distribution.

Response variable (Y)	Explanatory variables		Weight	AICc	ΔAICc
	PPA	LR			
Native pollinator					
Model 1	-	X	0.582	149.9	0.00
Model 2	X	X	0.179	152.3	2.35
Best model	log(Y) = -0.055+5.05*LR				
Diversity					
Model 1	-	X	0.346	150.1	0.00
Model 2	-	-	0.327	150.2	0.11
Model 3	X	-	0.183	151.4	1.27
Conditional average model	log(Y)=1.18+13.32*PPA+1.05*LR				

Source: Elaborated by authors.

Supplementary Material S3

Framework - expanded version.

https://github.com/lipeconomia/Material-suplementar

CAPÍTULO 3 – International trade of pollinator-dependent crops is increasing cropland in less developed countries[5]

Abstract

Global food demand of pollinator-dependent crops is leading to an unprecedented cropland expansion, especially in developing countries. However, it is unknown if such demand is more accentuated via international trade, especially regarding trade from less to most developed nations. Consequently, together with the traded agricultural products, ecosystem services, such as crop pollination, are virtually traded. Using information on 54 pollinator dependent crops markets for 115 countries between 1993 and 2015, we assessed how the mutual dependency on virtual pollination among countries is associated to their development level and how the trade of pollinated-dependent crops is increasing cropland areas throughout the world. As expected, virtual pollination exportation is greater from countries trading with high developed partners. In addition, developed nations were a more dependent on importation to meet their domestic consumption of virtual pollination. Most strikingly, the main driver of cropland expansion was exportation, but domestic consumption effect was more accentuated only in less developed exporting countries. Considering that less developed countries support pollinated-dependent crops consumption in more developed countries, their own consumption of such crops may be under risk. Increasing their cropland area to meet external demand may also depleting local ecosystem and associated services. Thus, an international coordination to protect biodiversity is needed, e.g., via adjustment in international prices for goods produced under pollinator-friendly management or transfer of financial resources and technologies of low impact on pollinators.

Keywords: Virtual pollination, Crop pollination, Pollinators.

[5] Este artigo terá como coautores Luísa G. Carvalheiro e Frédéric Mertens.

1. Introduction

The growth of world population and the will to have a healthier and diversified diet are increasing the demand for agricultural products (GODFRAY et al., 2010). Part of the food consumption in a given nation is met by national production and another is by international trade, which has been influenced by development pattern of countries (FAO, 2015). Taking into account the growing food price at international market, especially after 1990s (FAO, 2015), the economy of developing countries was historically based on an exportation-oriented agriculture (GOLLIN, 2010). On the other hand, most developed countries focused on importation of crops to meet their domestic consumption, which may be increasing their dependence on international trade for national food security. Lastly, while developed countries are consuming more and more diversified products (TILMAN et al., 2011), the poorest nations may be producing and exporting such products in order to boost local economies (MELLOR, 2000).

Products based on ecosystem services, such as pollinator-dependent crops, are traded due to the difference of comparative advantages associated to environmental condition between countries. For example, in some cases the reduced national food supply due to the scarcity or absence of some ecosystem services or natural resources important for crop production, such crop pollination, water provision, and land (BOMMARCO et al., 2013; HOEKSTRA and HUNG, 2002; REES, 1992) is compensated via importation. In other cases, this market contributes for countries that have no appropriate environmental conditions for production, for instance, European countries that import coffee, cocoa and tropical fruits to meet their domestic consumption. Thus, the environmental conditions in exporting countries for food production may be supporting consumption in other regions via international trade.

International price is defined at global market via interaction between supply and demand, regardless if the cost for managing such ecosystem services takes place. Countries that regulate farming activities to protect ecosystem and its services have a higher production cost if compared to countries that do not apply such environmental laws. For example, in Brazil, farmers must to conserve a given percentage of natural vegetation within their rural properties that varies from 20% up to 80% depending on the location of the farm in the Brazilian territory. Others examples are the regulation of use of pesticides, reforestation for carbon sequestration, among others. Countries that have not such restriction in farming activities may adopt conventional intensification, which is more harmful for ecosystems because it is associated to large monocultures and intensive use of chemical inputs. The strategy of selling products by prices that do not incorporate the environmental cost is called as environmental dumping, which may create fake competitive advantage.

Crop pollination is an ecosystem services played by wild (ecosystem service) or managed pollinator agents. This service is important for human food security (EILERS et al., 2011; ELLIS et al., 2015) because it supports the production of a number of crops, such as oilseeds, nuts, vegetables, fruits, among others (KLEIN et al., 2007). This service contributes in ca. 10 % of the global agricultural economy (GALLAI et al., 2009; LAUTENBACH et al., 2012) and is important for the agricultural production in several countries, such as China, India, USA, Brazil, Japan, and Turkey (LAUTENBACH et al., 2012). Although, it is an important ecosystem services, crop pollination is under threat due to agriculture intensification, especially due to cropland expansion (POTTS et al., 2010 and 2016).

To quantify the ecological footprint of countries on ecosystem, previous studies have measured the ecosystem service or natural resource used in the production process (e.g. land needed to support the consumption pattern, see REES, 1992; provision of water used in agriculture, see HOEKSTRA and HUNG, 2002). Embodied ecosystem services and natural resources within traded crop are classified as virtual traded services/resources (ALLAN, 1997). Although, there is still some debate (see MERRETT, 2003; and ALLAN, 2003), the concept of 'virtual service/resource' is useful in the academic and political scope. The natural dependence among world's regions may help to quantify and internalize the environment costs in crop price at international market (ALLAN, 2003; HOEKSTRA, 2003; QIANG et al., 2013), for example, those associated to environmental dumping. Previous studies used the concept of virtual water and virtual land to identify how foreign demand is pressuring ecosystem in exporting countries. Virtual water is the water used during the production process of a given commodity (see ALLAN, 1997; HOEKSTRA and

HUNG, 2005). The trade connections of volume of water associated to global food trade more than doubled between 1986 and 2007, especially because of the intensive demand of Asiatic countries (mostly by China) via soybean market (DALIN et al., 2012), a pollinator-dependent crop. Virtual land is another well-studied natural resource that, similarly to virtual water concept, is the land resource used in the agricultural production (see JINGQI et al., 2016). By this concept, land resource, a stationary resource, can be assessed as a flow via socioeconomic activities, for example, highlighting that the majority of this flow occurred between American countries (i.e., USA, Brazil and Argentina) to Asiatic nations (i.e., China and Japan) over 2007-2011 (JINGQI et al., 2016).

Both virtual water and virtual land are well-studied natural resources, but virtual pollination services, to our knowledge, were not received any attention by academy. Here, we proposed the concept of virtual pollination as a service provided by pollinators for the production of agricultural commodities. Virtual pollination is important because, first, it might indicate how human food consumption is threatened by the current declining in pollinators. Some crop systems are largely dependent on pollinator because such service is a way to close yield gaps (GARIBALDI et al., 2016b). Thus, the absence of pollination agents may compromise overall production even with abundance in water and cropland (e.g., almonds, coffee, cocoa, fruits, and some vegetables). Second, virtual pollination can help to identify exporting countries in which conservation of already existent vegetation areas is crucial for sustainability of national and international food security. Third, virtual pollination may also contribute for international coordination to support biodiversity by adoption of pollinator-friendly practices in crop systems of exporting countries, for example, by increasing revenue with certification of products produced under pollinator-friendly practices (TREWEEK et al., 2006), by transferring financial resources to develop or import new technologies of low impact on pollinators to developing countries (DICKS et al., 2016; POTTS et al., 2016), or by restricting deforestation areas (see Brazil's Soy Moratorium, GIBBS et al., 2015).

Global food production is leading to an unprecedented cropland expansion worldwide, especially areas dedicated to pollinator-dependent crops (AIZEN et al., 2008 and 2009). Such impact is a driver of deforestation and biodiversity loss in producing regions (MAYER et al., 2005; LENZEN et al., 2012) jeopardizing ecosystem and associated services (POTTS et al., 2016) that are important for agricultural systems. Cropland dedicated to pollinator-dependent crops has been increased over last decades, especially in less developed countries (AIZEN et al., 2008 and 2009). Cultivated area of such crops was 130% greater in developing nations compared to developed nations in 2006 (AIZEN et al., 2009). Pollination services are important for the production of a number of exporting-crops, such as coffee, cocoa, soybean, and tropical fruits, most growing in developing nations (LAUTENBACH et al., 2012). Moreover, production of pollinator-dependent crops may be attractive at international market, because their global price is five times higher than those non-dependent crops (e.g., rice, wheat, corn, tubers, among others) (GALLAI et al., 2009). Although international market of pollinator-dependent crop is crucial to understand cropland pattern, trade was not considered by previous studies at global scale (see AIZEN et al., 2008 and 2009; GALLAI et al., 2009; LAUTENBACH et al., 2012).

Here we aim to understand the virtual pollination flow taking into account the influence of the countries' development on the dynamic of trade. First, considering the supply perspective, we assessed if virtual exportation of pollination is associated to the development level of exporting countries (objective 1). We expect that virtual exportation of pollination is higher in less developed countries. In addition, we tested if this flow is associated to the development level of trading partners (objective 2). We expect that virtual exportation of pollination is higher from less to most developed countries. On the perspective of demand, we tested if the countries' dependence on virtual importation of pollination is associated to its development level (objective 3). We expect that dependence on virtual importation of pollination increases inasmuch as also increases the development level of importing countries. In addition, to assess whether the trade is more accentuated from less to most developed countries, we tested if virtual importation of pollination is influenced by the difference in development level of importing countries and of their trading partners (objective 4). We expect that virtual importation of pollination increases with the difference between development level of importing countries and of their trading partners. Finally, taking into account the impact of trade on cropland expansion, we tested if the demand of pollinated-dependent is expanding cropland of such crops in exporting countries (objective 5). In addition, we also assessed whether these effects are boosted by the development level of countries (objective 6). Here, we expect that the effect of exportation on cropland expansion is more accentuated than domestic consumption effect, especially in less developed exporting countries. We presented flow maps to illustrate virtual flow of pollination between countries. In order to investigate if the virtual flow of pollination has a different pattern compared to overall agricultural trade, we also assessed the dynamic of all crops (i.e., dependent and non-dependent on pollinators) in international trade.

2. Methods

We used the information on cropland, trade and production of 54 pollinator dependent crops at national level for 115 countries between 1993 and 2015 taken from Food and Agriculture Organization of the United Nations (FAO, 2018) (Supplementary Material S4). FAO (2018) is one of the most comprehensive and available global dataset on cropland, trade and production of crops. However, this dataset presents inconsistencies in information especially due to a range of countries that report information gathered with different methods of data collection (GILL, 1993). We detected some inconsistencies in FAO dataset (2018) between the information of “Trade dataset”, which consists in information on crop annually traded presented by reporting countries, and those in the “Detailed Trade Matrix dataset”, at which information on trading partners is added. For several countries, it is not possible to identify their trading partners in Detailed Trade Matrix because a part of the information is allocated at unspecified areas. Another inconsistence is that the total importation and exportation differs between both datasets, being the Trade dataset more robust in information for the majority of countries. Thus, if the values in the Detailed Trade Matrix dataset exceeded the values in Trade dataset, the exceeded-value was aggregated in second dataset. To avoid inconsistencies, Detailed Trade Matrix dataset was only used to calculate Human Development Index of trading partners and to create flow maps (see below), while adjusted Trade dataset was used for all others measurements (for more details see Supplementary Material S4).

We focused on post 1990 data (1993 and 2015) because in this period several initiatives for biodiversity and nature conservation emerged at national and global scale (e.g., Eco 92 and Conventional on Biological Diversity, International Pollinator Initiative, Kyoto Protocol, among others). However, for the region Belgium-Luxembourg, detailed information at national level was only available after 2000, so for statistical analysis both countries were maintained as one region.

2.1. Calculating virtual pollinators

The benefit of crop pollination to society can be measured based on the difference in yield in individual plant isolated (or exposed to a lesser extent) vs exposed to pollinators (single species or assemblage of pollinators) (see LISS et al., 2013). Taking into account that the contribution of pollinator to production varies significantly across cultivated plants, pollinator dependence rate for major world crops was gathered in Klein et al. (2007) and Gallai et al (2009). While we recognize that different varieties of the same crop species may have different dependence levels (e.g., CARVALHEIRO et al., 2011 and 2012), and different regions may use different varieties, due to lack of information at variety level, we assumed that pollination dependence level was similar across cultivars of a single crop species for the analyses here presented. In addition, pollinator contribution to crop production also varies across landscapes and by local cropland management (e.g., conventional or organic management), for example ranging from 10% up to 40% for soybean, coffee, rapeseed (KLEIN et al., 2007). However, detailed information on production dedicated to trade is not available by landscape or by cropland management in FAO dataset, being impossible to calculate the traded part of overall crop production that was produced under pollination services provided by natural areas. We recognized that all those effects do exist, but, due to lack of information, we assume here that pollinator dependence rate represents the average contribution of landscape configuration and cropland management to crop production via pollination services. After the publication of Klein et al (2007), a number of published studies assessed the pollinator contribution for several crops. One of those crops is common bean (Phaseolus vulgaris L.) that was described as having little dependence by Klein et al. (2017), but considering recent studies that assessed the pollinator contribution in terms of yield and crop quality (see KINGHA et al., 2012; MASIGA et al., 2014; RAMOS et al., 2018; Chapter 1), we considered here that this crop has medium level of pollinator dependence.

Virtual flow of pollination is here defined as the proportion of overall production resulting from the action of pollinators. National production is dedicated to both domestic market (red arrow) and exportation (green arrow) (see Fig. 17-A). Following the biophysical method proposed by Gallai et al. (2009), we calculate the virtual production of pollination by multiplying the dependence rate and the production quantity (t/year) of each crop in each country (see green area in Fig. 17 – B). Thus, overall virtual exportation of pollination of a given country *i* (VPE_i) (ton/year) was calculated as the sum of the product of annually exportation of each pollinator-dependent crop *m* ($EX_{m,i}$) (ton/year) times their respective pollinator dependence rate (Dm) ($VPE_i=\sum EX_{m,i}*D_m$) during 1993 and 2015 (see Fig. 17-C). Similarly, overall virtual importation of pollination of a given country *i* (VPI_i) (ton/year) was calculated as the sum of the product of the annually importation of all pollinator-dependent crop *m* ($IM_{m,i}$) (ton/year) times their respective pollinator dependence rate (Dm) ($VPI_i=\sum IM_{m,i}*D_m$) during 1993 and 2015 (Supplementary Material S4).

The virtual domestic consumption of pollination in a given country *i* (C_i) (ton/year) was also calculated as a sum of product between the national production of each pollinated-dependent crops *m* ($Q_{m,i}$) (ton/year) plus its net values of international trade ($IM_{m,i}$ - $EX_{m,i}$) (ton/year), and the respective pollinator dependence rate of such crops *m* (D_m). ($C_i = \sum\{[Q_{m,i} + (IM_{m,i} - EX_{m,i})] * D_m\}$). The dependence of an importing country *i* on virtual importation of pollination to meet its virtual domestic consumption of this service (DVP_i) was calculated by the ratio between virtual importation and virtual domestic consumption of pollination ($\sum(VPI_i)/ C_i$). The dependence of countries on virtual importation of this service was calculated by the annually average of values over the period between 1993 and 2015 (Fig. 17-C).

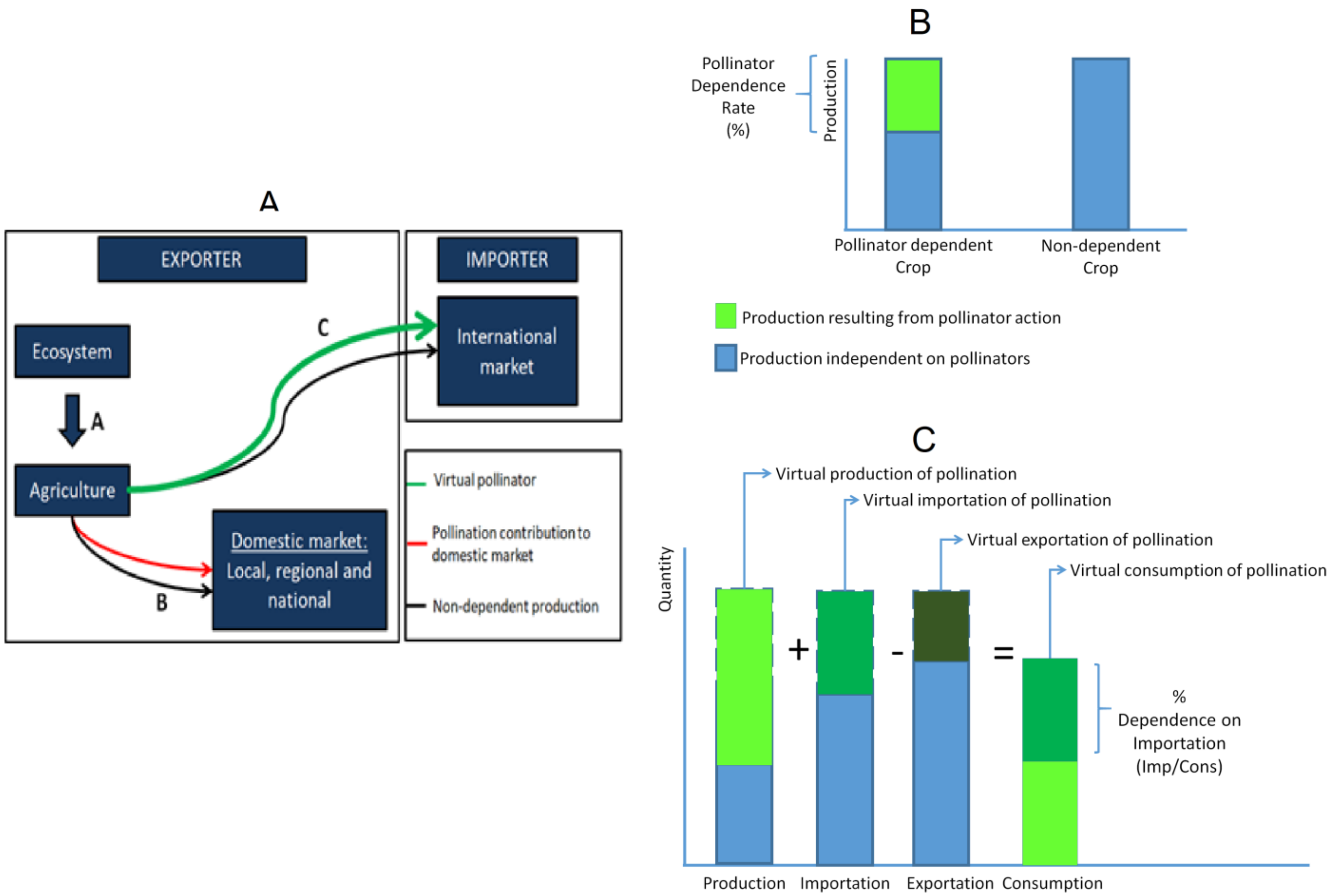

FIG. 17 – Virtual flow of pollination. A - Ecosystem provides several services to agriculture, including crop pollination (Arrow A), green and red arrows represent the crop production resulting from pollinator action that feeds international (i.e., virtual pollinator exportation) and national markets, respectively, and black arrows indicate the crop production that is independent on pollinators. B – Dependence rate is given as a percentage on the total production of a given pollinator-dependent crop that is resulted from pollinator action (green area). C – Dependence on importation is given by the ration between virtual importation and virtual consumption of pollination.

Source: Elaborated by authors.

2.2. Countries' development level

Food demand of countries is associated to a range of human development aspects, for example, the standard of life that can be represented by the income per capita (POLEMAND and THOMAS, 1995; TILMAN et al., 2015) and the level of education that is positively associated to a healthful dietary (VOGEL et al., 2016; SCHOUFOUR et al., 2018). The Human Development Index (HDI) is an indicator of development level of countries that is broadly used in academic and political scopes and encompasses three dimensions of human development: standard of life, knowledge and health. The development level of countries and their trading partners were measured by the Human Development Index (HDI) because those socioeconomic aspects of human development are associated to the demand and consumption of pollinated-dependent crops that may end up influencing the international trade of virtual flow of pollination. Information on HDI was gathered from United Nations Development Programme (UNDP, 2018).

The development level of a given country i (HDI_i) was calculated by the annually average of its Human Development Index during 1993 and 2015. The development level of their trading partners was calculated considering all trading partners with available data in the Detailed Trade Matrix of FAO (2018). The development level of the trading partners of a given exporting country *i* was calculated by the sum of the annually average Human Development Index of all trading partners *j* ($HDI\_exp_{i,j}$) weighted by their respective proportion in overall virtual exportation of pollination ($\sum(HDI\_exp_{i,j})*(VPE_{i,j}/VPE_i)$) during 1993 and 2015. Similarly, the development level of the trading partners of a given importing country *i* was in function of their annually average Human Development Index (HDI*j*) and their proportion in overall virtual importation of pollination ($\sum(HDI\_imp_{i,j})*(VPI_{i,j}/VPI_i)$) during 1993 and 2015. The HDI associated to Unspecified Areas in the Detailed Trade Matrix dataset was considered as zero.

2.3. Cropland expansion, exportation and domestic consumption of pollinated-dependent crops

Cropland expansion in a given country *i* (CL_i) was calculated as the ratio between the area harvested at national-level of all pollinator-dependent crops in 2015 and 1993 ($CL_{i,2015}/CL_{i,1993}$). As the growth in cropland occurs to meet both international and national markets, the pressure of international market on cropland in a given country *i* was calculated by the variation of overall exportation of pollinated-dependent crops between 1993 and 2015 ($\Delta EX_i = EX_{2015}/EX_{1993}$). The pressure of domestic consumption of pollinated-dependent crops on cropland of a given country *i* (ΔC_i) was measured by the variation of domestic consumption of such crops, $C_i = \sum[Q_{m,i} + (IM_{m,i} - EX_{m,i})]$, between 1993 and 2015 ($C_{i,2015}/ C_{i,1993}$).

2.4. Statistical analyses

To assess if virtual exportation of pollination (VPE_i) is influenced by the development level of exporting countries (objective 1) and by the development level of their trading partners (objective 2), we used a linear regression taking the annually average of HDI of exporting country (HDI*i*) and of their trading partners (HDI_exp*i,j*) as independent variables. To account for the influence of development level of trading partners on the effect of the development level of exporting countries on its virtual exportation of pollination, we included a two-way interaction between both variables. We applied a Box-Cox transformation (bc) on the response variable for normalization of residuals (λ=0.1) (Table 10 in S5).

We used a linear regression to assess the countries' dependence on virtual importation of pollination to meet their virtual domestic consumption (DVP_i), taking into account the annually average of Human Development Index of importing countries (HDI_i) as independent variable (objective 3). We applied a Box-Cox transformation on the response variables to normalize residuals (λ=0.04) (Table 11 in S5).

To assess the virtual importation of pollination (objective 4), we used a linear model with the overall virtual importation of pollination (VPI_i) as response variable and the ratio between the development level of the importing country and of their trading partners ($HDI_i/HDI\_imp_{i,j}$) as independent variable. The response variable was log-transformed to normalize residuals (Table 12 in S5).

The cropland expansion is dependent on both national and international markets, so to compare the effects of both demands on cropland dedicated to pollinator-dependent crops in exporting countries (objective 5) and if these effects are boosted by the development level of exporting countries and of their trading partners (objective 6), we used a linear model taking into account cropland expansion of all crops (CL_i) as response variable and as independent variables the variation of domestic consumption of all pollinated-dependent crops (ΔC_i), variation of overall exportation of pollinated-dependent crops (ΔEX_i), development level of exporting countries (HDI_i) and of their trading partners ($HDI\_exp_{i,j}$). We applied a standard score transformation (z-score) on domestic consumption and exportation to compare which component of the demand on pollinator-dependent crops is the main driver of cropland expansion. We included a two-way interaction between both variables to test whether domestic consumption effect in exporting countries is influenced by their development level. We included a two-way interaction between the exportation and the development level of trading partners to verify if the demand of most developed countries is pressuring cropland in exporting countries. The variable cropland expansion (ratio between present and past) was log-transformed to normalize residuals (Table 13 in S5).

All statistical analysis were carried out with R (R DEVELOPMENT CORE TEAM, 2017), using the 'lm' function for linear regression, the 'MASS version 7.3-49' for Box Cox Transformation (RIPLEY et al., 2018), and the 'visreg version 2.3-0' for model visualization (BREHENY and BURCHETT, 2016).

2.5. Flow maps

To create flow maps of virtual flow of pollination, we used the Detailed Trade Matrix from FAO (2018) and the software QGIS 2.18.2 (QGIS DEVELOPMENT TEAM, 2018), using arrows to indicate the flow from exporting to importing countries and width to denote the quantity traded. Finally, we used the world borders map provided by Thematic Mapping (TM, 2018).

3. Results

The largest exporter and importer of virtual pollination were USA and China, respectively (Table 9). Some developing countries were important for virtual exportation of pollination (i.e., Brazil, Argentina, China, Mexico, Cote d´Ivoire, Chile, and Paraguay). Japan, USA, Germany, and Netherlands were important nations for virtual importation of pollination (Table 9 and Supplementary Material S4).

The main trading partners (i.e., demanded more than 50% of their virtual exportation of pollination) of the USA were China, Japan, and Mexico (Figure 18). For Brazil and Argentina, only China demanded more than 50% of their total virtual exportation of this service. Spain played an important role as a virtual exporter of such service in Europa, largely exporting to United Kingdom, France, and Germany.

Neither the development level of exporting countries (objective 1) nor of their trading partners described the virtual exportation of pollination (objective 2) (Fig. 18 and Table 10 in S5). Both variables were only responsible for 4.6% of the variance of virtual exportation of pollination. More than a half of such exportation was dominated by five countries (i.e., USA, Brazil, Argentina, Spain, and Canada). In addition, development level of exporting countries and of their trading partners was not significant to explain the overall exportation of crops, including non-dependent crops (Table 10 in S5).

Table 9 – Trade of total crops and virtual pollination over 1993-2015.

Rank	Total exportation of crops		Total virtual pollination exportation		Total importation of crops		Total virtual pollination importation	
	countries	millions t	countries	millions t	countries	millions t	countries	millions t
1	USA	2737.22	USA	213.85	China	1122.41	China	199.55
2	France	811.86	Brazil	135.83	Japan	809.77	Germany	101.07
3	Canada	765.64	Argentina	48.91	Germany	484.14	USA	89.05
4	Brazil	713.83	Spain	46.12	USA	460.34	Netherlands	72.32
5	Argentina	690.05	Canada	43.83	Netherlands	443.81	Japan	49.21
6	Australia	503.80	Net	33.75	Mexico	413.66	France	39.80
7	Ukraine	308.51	Mexico	33.38	Spain	358.86	UK	38.58
8	Germany	296.37	Italy	29.90	South Korea	336.85	Spain	37.21
9	Russia	271.83	France	29.89	Italy	322.16	Russia	34.46
10	China	265.27	Cote d'Ivoire	25.06	Belgium-Luxemburg	318.94	Mexico	33.57
11	Spain	227.72	China	24.13	Egypt	304.67	Belgium-Luxemburg	32.04
12	Netherlands	213.88	Chile	19.29	UK	221.53	Italy	25.19
13	Mexico	133.81	Paraguay	16.20	Saudi Arabia	219.08	Canada	23.25
14	Belgium-Luxemburg	130.38	Belgium-Luxemburg	16.05	Brazil	202.24	Turkey	14.78
15	India	129.12	New Zealand	13.16	Algeria	190.43	Portugal	12.82
Others countries		1995.00		201.37		3533.18		243.69
Total		10194.31		930.70		9742.06		1046.59

Source: Elaborated by authors.

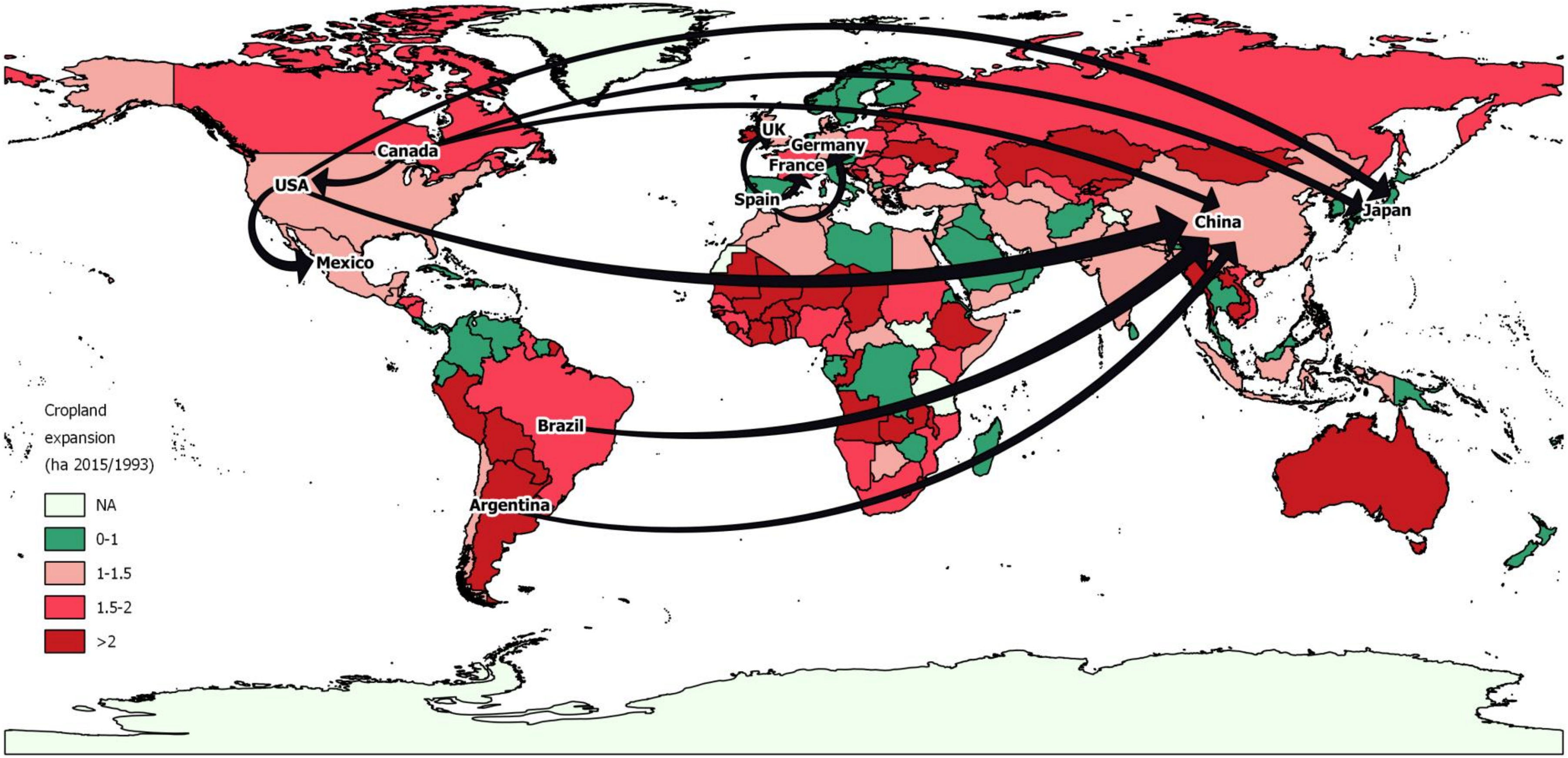

FIG. 18 – Largest exporters of virtual pollination and their main trading partners. The selected exporting countries represent more than 50% of the virtual exportation of pollination between 1993 and 2015. Map illustrates the cropland expansion in all countries. Arrow width indicates the amount of virtual exportation of pollination that varied from 5 to 66 million of tones in this trade flow.
Source: Elaborated by authors.

Countries with higher development level depended more on virtual importation to meet their domestic consumption of virtual pollination (objective 3) (Fig. 19 and Table 11 in S5). Eight countries presented dependence above 80% including four with an intensive importation that resulted in an annually average of the ration importation/consumption of virtual pollination above 1 (i.e., Singapore – 1.4, Netherlands – 1.1, Estonia – 1.1 and the bloc of Belgium and Luxembourg – 1.0). This result is likely associated to countries that play a role as intermediate traders, for example, importing virtual pollination to further export, a phenomenal named as secondary exportation.

The most dependent countries on virtual importation of pollination (VPI) (i.e., that with more than 80% of domestic consumption met by importation of virtual pollination) were both developed and developing countries. European countries presented the highest dependence on VPI, especially Ireland (main trading partner were Netherlands, UK, and France), Belgium-Luxemburg (trading with France, Canada, USA, Brazil and Netherlands), Norway (traded with Brazil), and Estonia (traded with Poland, Netherlands, Cote d'Ivoire, Ghana). The main developing countries that present a highest dependence on VPI were Bahrain (traded with Jordan, Syria, and Iran), Singapore (traded with Malaysia and Indonesia), and Botswana (traded with South Africa). The majority of countries presented less than 20% of the dependence level on virtual importation of pollination.

Comparing the virtual pollination dependence of countries with dependence on importation of overall crops, both dependences were positively associated to development level of countries (Fig. 20). Although both presented the same trend, the dependence on virtual pollination importation was more accentuated inasmuch as development level of countries increases.

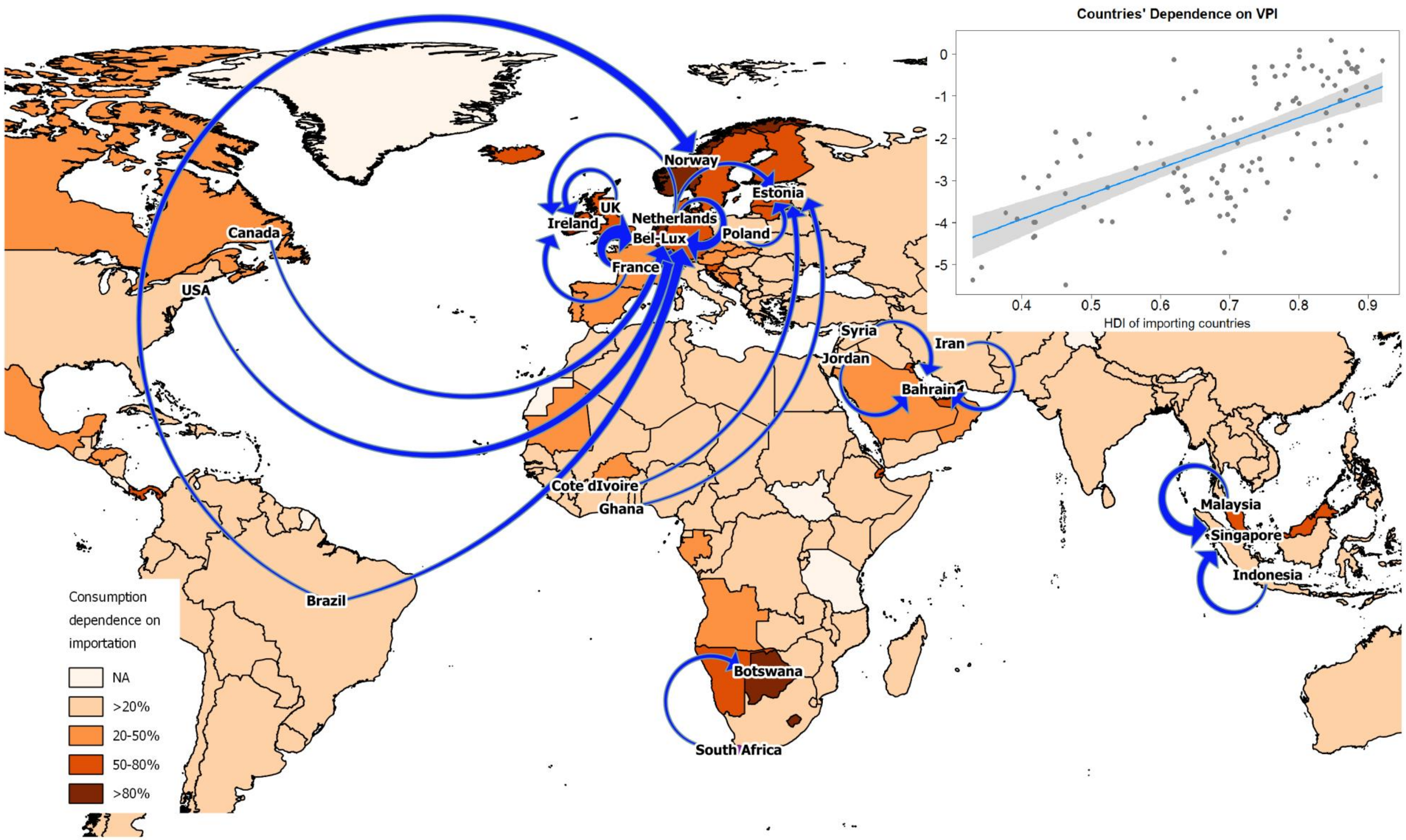

FIG. 19 – Countries' dependence on virtual importation of pollination and the flow of virtual importation of pollination of the most dependent countries. Arrows illustrate the trade of most dependent countries on virtual importation of pollination (i.e., > 80% of domestic consumption of such service based on importation) and their main trading partners (i.e., supply more than 50% of their virtual pollination demand). Arrow width indicates the total quantity of virtual pollination traded over 1993-2015 that varied from 0.03 to 4 million of tones in this trade flow. Linear model depicts the association between the countries' dependence on virtual importation of pollination (i.e., annually average of the ratio between importation and domestic consumption of virtual pollination over 1993-2015) and their development level (i.e., annually average of Human Development Index (HDI) over 1993-2015).
Source: Elaborated by authors.

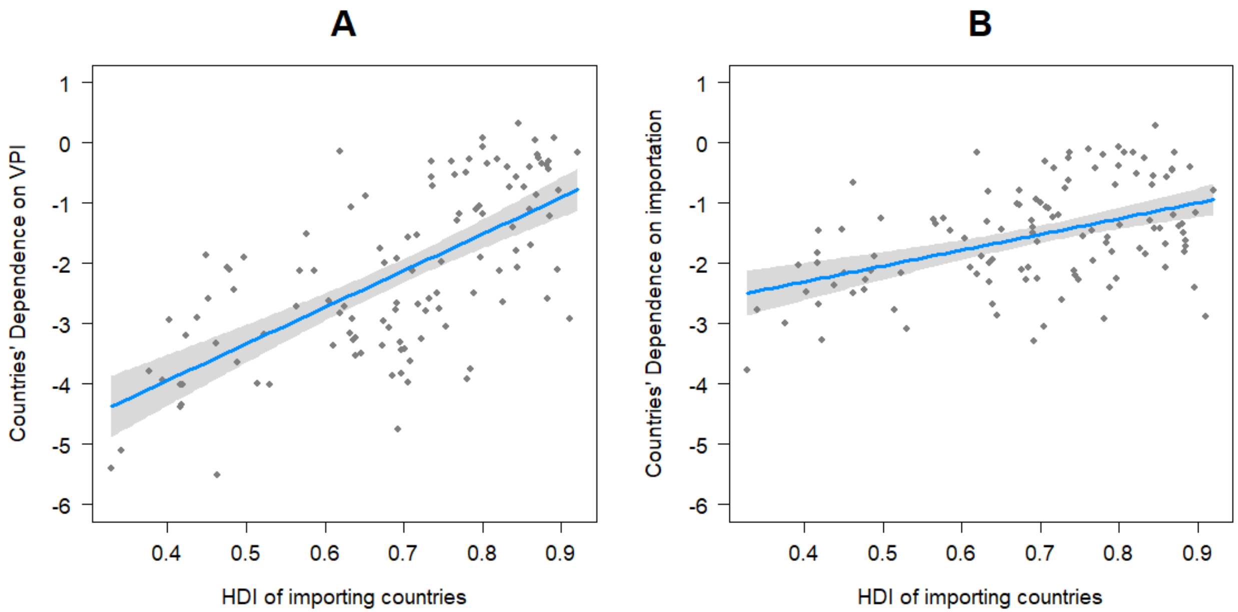

FIG. 20 – Effect of development level of importing countries on their dependence on virtual importation of pollination (DVP) and on overall importation of crops. Countries' dependence is measured by the annually average of the ratio between importation and domestic consumption of virtual pollination 'A' and of overall crops 'B' over 1993-2015. Development level of countries was measured by the annually average of the Human Development Index over 1993-2015. Graphics were based on equations from Table 11 in S5.
Source: Elaborated by authors.

The virtual flow of pollination was more intensive from less to most developed countries (objective 4) (Fig. 21 and Table 12 in S5), indicating that more developed are demanding such service from less developed nations. Overall crop importation, including non-dependent crops, was also positively associated to the difference between the development levels of trading partners (Fig. 22). Both trends were similar, but the effect of the difference between development levels of countries was more accentuated on virtual importation of pollination.

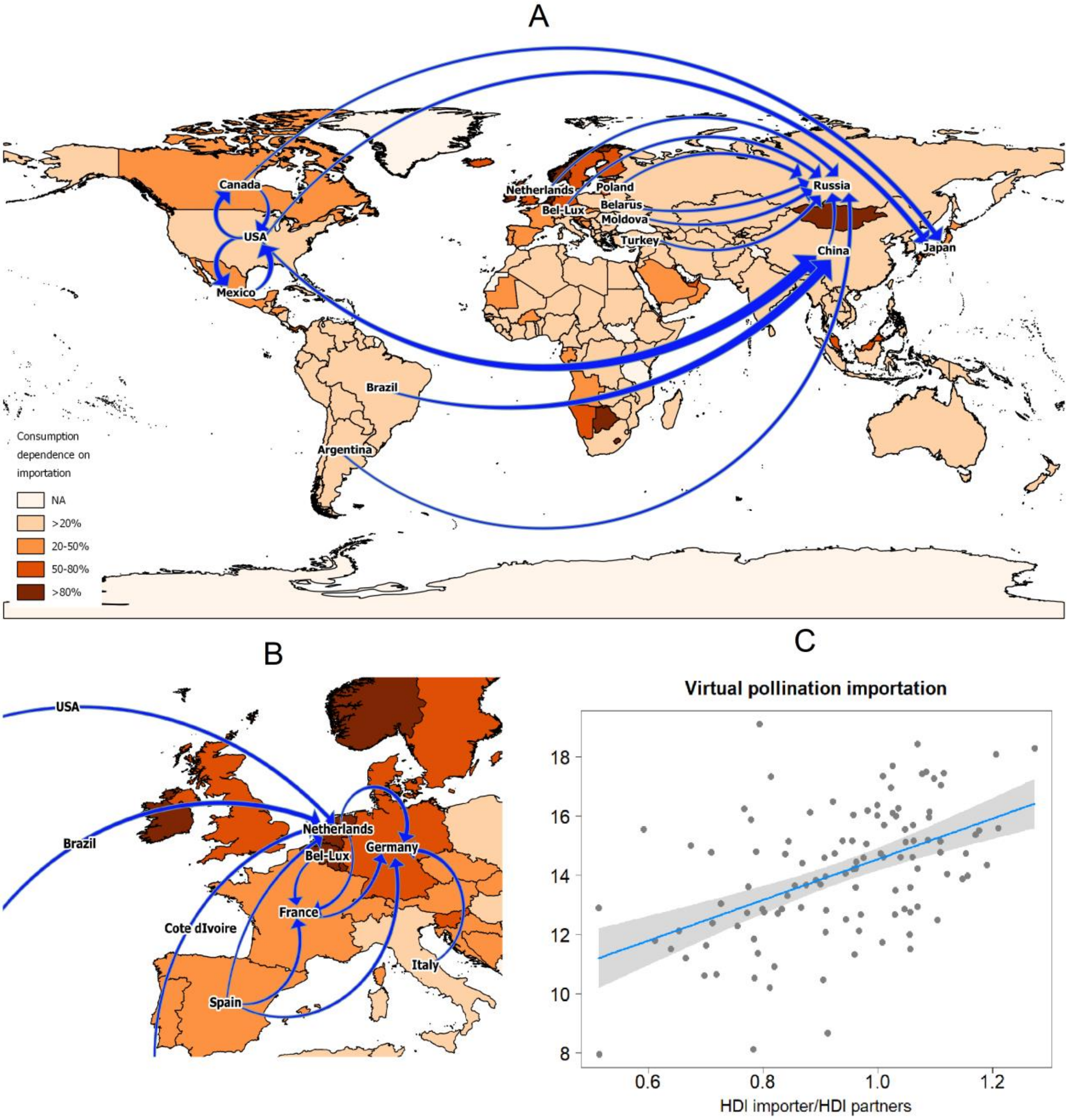

FIG. 21 – Relationship between the difference in development levels of importing countries and their trading partners and amount of virtual importation of pollination. Maps 'A' and 'B' indicate the countries' dependence on virtual importation of pollination and the flow of such services between the largest importers (i.e., 50% of global VPI) and their main trading partners (i.e., supply more than 50% of their virtual pollinator demand). Arrow width indicates the amount of virtual importation of pollination between 1993 and 2015 that varied from 1 to 80 million of tones in this trade flow. 'C' depicts the association between virtual importation of pollination of countries (i.e., sum VPI over 1993-2015) and the ratio between the annually average of their development level and of their trading partners over 1993-2015. Shaded area represents the 95% confidence interval.

Source: Elaborated by authors.

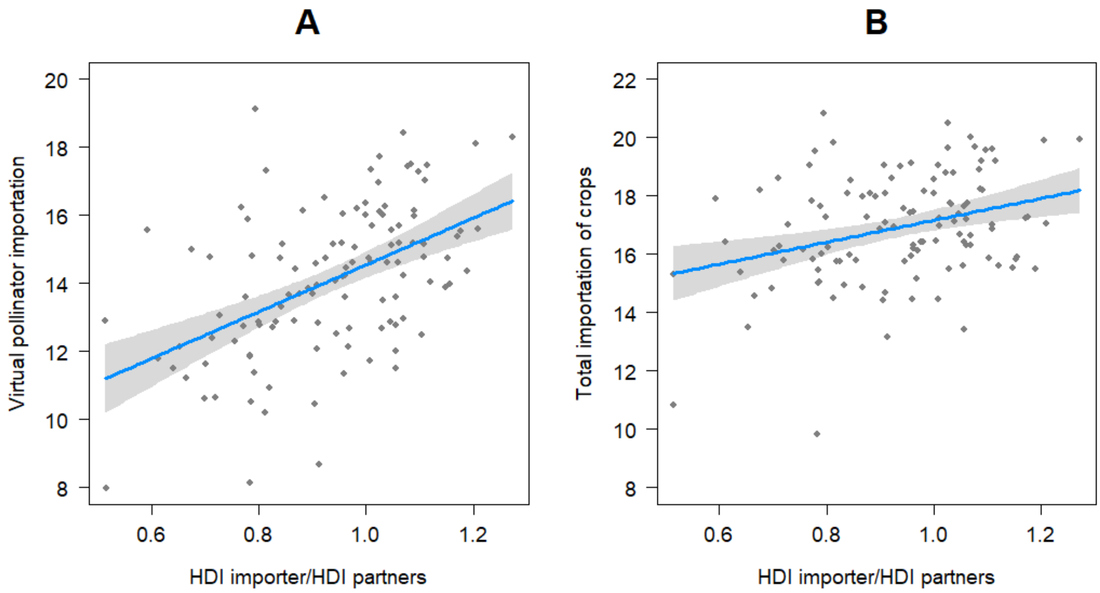

FIG. 22 – Effect of the difference between the development level of importing countries and of their trading partners on virtual importation of pollination and on overall importation of crops. Response variables were the virtual importation of pollination and overall importation of crops, including non-dependent crops, of countries over 1993-2015. Independent variable was the annually average of the ration between the Human Development Index of importing countries and of their trading partners over 1993-2015 (HDI/HDI_imp). Graphics were based on equations from Table 12 in S5.
Source: Elaborated by authors.

Between 1993 and 2015, the main driver of expansion in cropland dedicated to pollinator-dependent crops was the variation in exportation (objective 5) regardless the development level of their trading partners (objective 6) (Fig. 23 and Table 13 in S5). Consumption effect was influenced by the development level of exporting countries. The effect of exportation on cropland expansion was more accentuated (i.e., 0.27) compared to consumption effect in less developed countries (i.e., for HDI of 0.4, the effect was 0.21) and in most developed countries (i.e., for HDI of 0.8, the effect was -0.09). Thus, the effect of domestic consumption was similar to exportation in less developed countries (see slope in Fig. 23 and the coefficient in equation in Table 13-S5).

Countries with intensive cropland expansion due to pollinated-dependent crops were Uruguay (traded with China), Cote d’Ivoire (traded with USA, Netherlands, and India), Australia (traded with China, Japan, Pakistan, Netherlands, and Belgium-Luxemburg), Estonia (traded with Finland and Russia), and Lithuania (traded with Russia) (Fig. 23).

Analyzing cropland expansion of all crops, including non-dependent crops, exportation of overall crops presented a similar effect on cropland expansion comparing to the subgroup of pollinated-dependent crop (Fig. 24). Such trend also was independent on the trading partners’ development. However, differently to the effect of domestic consumption on cropland expansion of the subgroup of pollinated-dependent crops, the effect of consumption on cropland expansion dedicated to all crops was independent on development level of exporting countries.

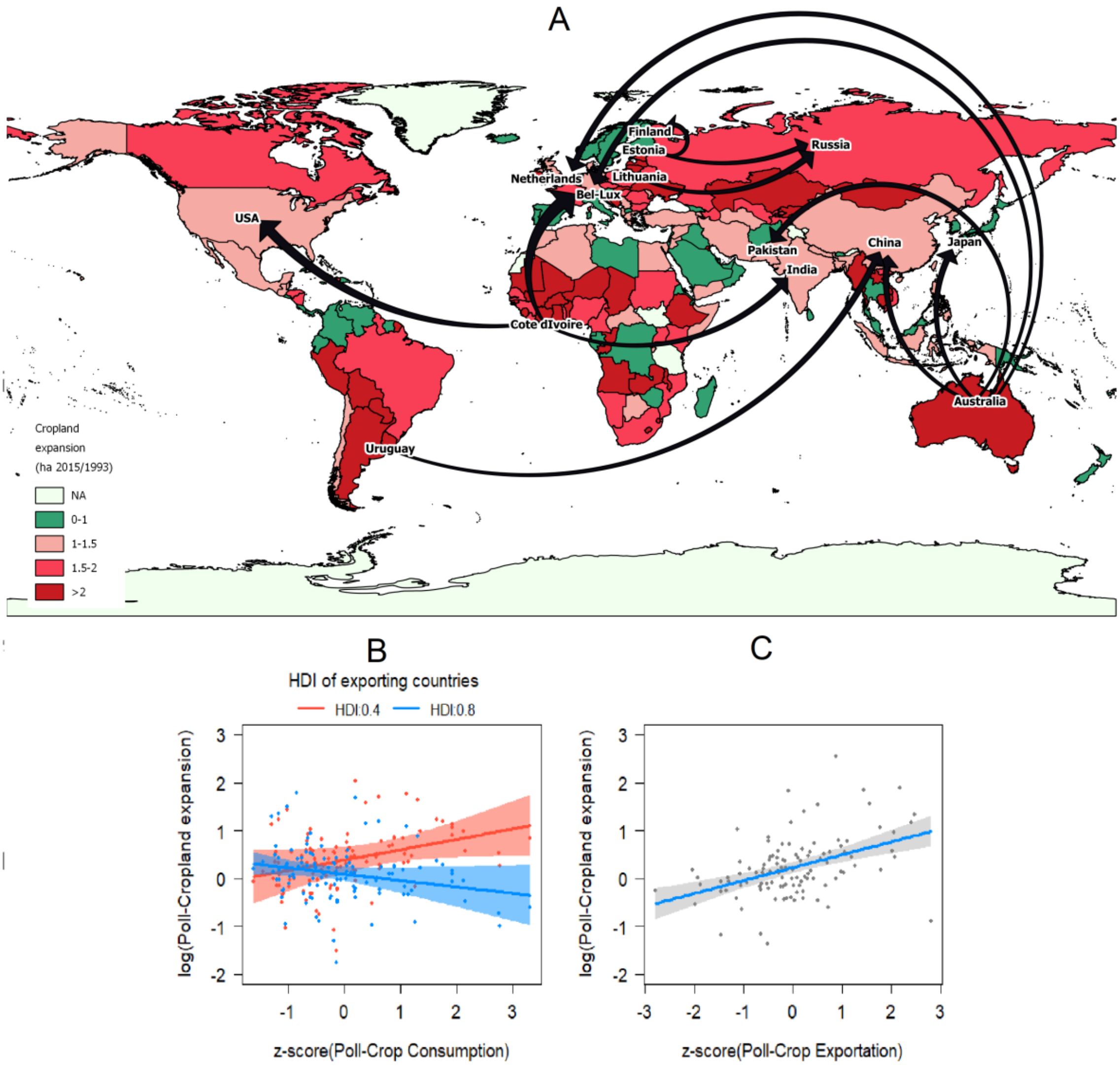

FIG. 23 – Effect of domestic consumption and exportation of pollinator-dependent crops on cropland expansion. 'A' depicts virtual exportation of pollination from countries with the highest expansion in cropland (> 500%) to their main trading partners (i.e., those that demand more than 50% of such service). We include Cote d'Ivoire to account the main African exporter of virtual pollination. Arrow width indicates the amount of VPE over 1993-2015, which varied from 0.1 to 5 million tones in this subgroup of exporting countries. 'B' depicts the association between cropland expansion and domestic consumption, taking into account the development level of exporting countries. 'C' indicates the effect of exportation on cropland expansion in exporting countries. The effect of exportation is stronger than consumption even in less developed countries (see slope).
Source: Elaborated by authors.

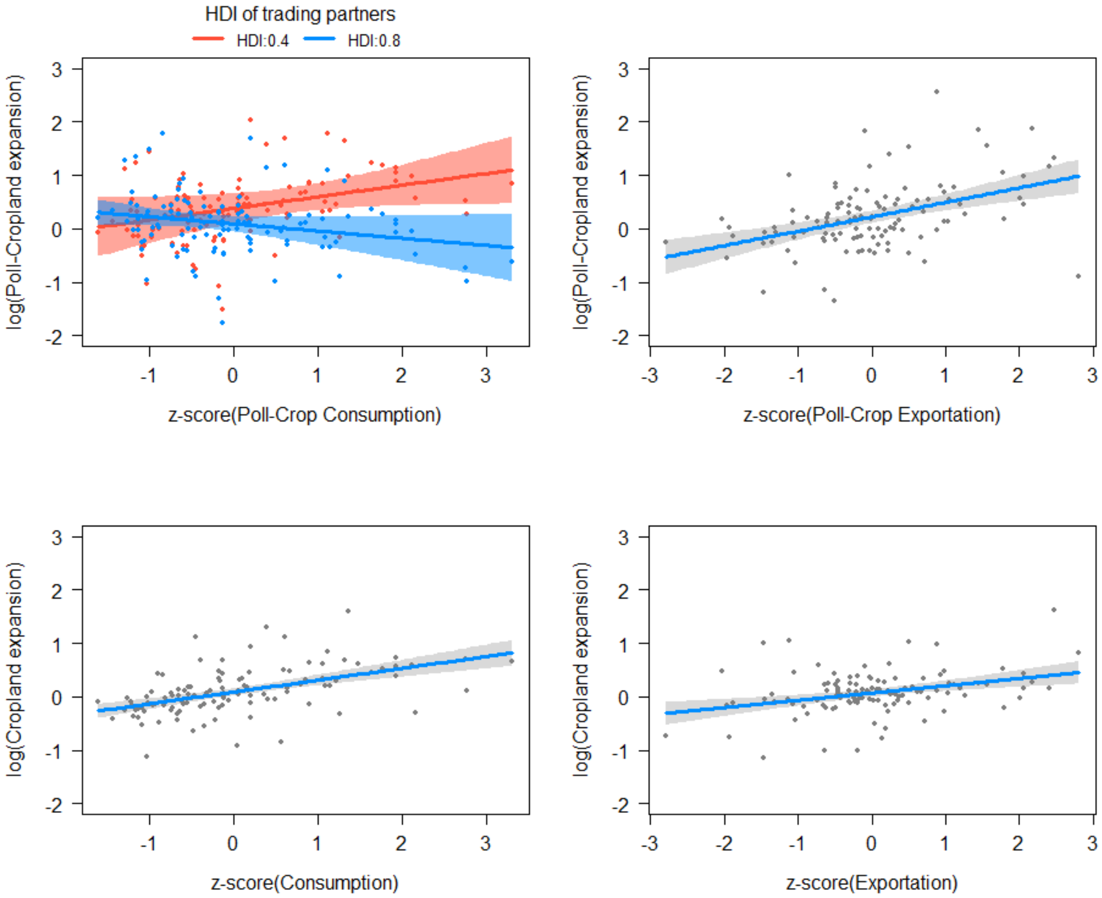

FIG. 24 – Effect of exportation and domestic consumption on cropland expansion dedicated to pollinated-dependent crops and total crops, including non-dependent crops. Development level of countries was based on annually average of human development index over 1993-2015. Response variables in all models were log-transformed to normalize residuals. Domestic consumption and exportation in all models were transformed with standard score (z-score) in order to compare the effect of both variables on cropland expansion.
Source: Elaborated by authors.

4. Discussion

The world's nations are mutually dependent on their natural services that are important for agricultural production and human wellbeing. Similarly to virtual water and virtual land, this study showed that virtual pollination is a very important ecosystem service that support global demand of agricultural products via international market. Our results demonstrated that the most developed countries are more dependent on importation to meet their domestic consumption of virtual pollinator. All nations have limited resources to apply in economic activities, so traditionally countries in a development trajectory displace resources from farming activities to more complex production systems (such as industry and services). Thus, domestic demand for food and others agricultural products is met by importation. In addition, some crops are not feasible in temperate zone, such as coffee, cocoa, and tropical fruits, so importation is crucial for consumption of these products.

The flow of virtual pollination is more intensive from less to more developed countries. International price of pollinator-dependent crops is five times higher than non-dependent crops (GALLAI et al., 2009). As development is associated to increased purchase power of nations, thus richest nations are demanding from less developed exporting regions their pollinated-dependent crops and its associated pollination services. Countries with lowest purchase power have a very limited access on international market. Thus, in such countries, the competition between national and international demand is more accentuated in terms of their resources.

International trade and domestic consumption of pollinated-dependent crops have different effects on cropland areas in exporting countries. Our results complement previous studies that demonstrated a global growth in cropland dedicated to pollinator-dependent crops (AIZEN et al., 2008 and 2009). We demonstrated here that such impact relies on the type of demand (external or internal) and on development level of exporting countries. Exportation of pollinated-dependent crops was not influenced by development level of trading partners likely due to such crops are traded for many purpose. For example, soybean is traded to feed human society and cattle production in both developed and developing nations. Thus, the association with development level of partners is more difficult to predict. On the other hand, consumption is more tied to national socioeconomic conditions, so a clear association with cropland expansion was detected considering development level of exporting countries. Domestic consumption in the most developed exporting countries negatively influenced cropland expansion likely due to such consumption being supported via importation. In less developed countries, access to international market is a difficult barriers for consumption, thus the competition of land resource is more accentuated. Finally, this cropland expansion might be affecting local ecosystem via deforestation.

International trade of virtual pollination is crucial for the food security in a number of countries. Global benefits of pollination services are concentrated in a small group of countries taking into account the value of this service on national agricultural production (LAUTENBACH et al., 2012). In addition, strategies to compensate ecosystem depletion are even more needed in those countries because it can compromise their food availability and security at national market if the exportation became more intensive. Thus, guiding trade policies to protect pollinators require the quantification of how importation of the most developed countries is pressuring cropland expansion in exporting regions. In addition, it is also important to recognize the international responsibility in natural resources depletion (UNEP, 2013).

4.1. International governance for pollinator protection

International environmental regulation is a complex and conflicted process because the development of northern nations was based on a historical process of exploration of natural capital in the southern nations, being a number of them ancient colonies of developed countries (ALMEIDA et al., 2010). Developing countries are demanding now their right of development and their national sovereignty to explore their own natural capital to eliminate poverty, to ensure national food security, to stimulate economic growth, among others goals. In general, developing countries have low financial capacities to use sustainable technologies to increase agricultural productivity that could safe new cropland areas. One example is ecological intensification that encompasses a range of alternatives to manage ecosystem services in order to increase crop yield (BOMMARCO et al., 2013). Cropland expansion due to trade of pollinator-dependent crops may be is pressuring ecosystem and associated services in exporting countries. Thus, it is important to foment international policies to safeguard natural capital, ecosystem, biodiversity and associated services, and to ensure food security and economic growth.

International demand may increase environmental degradation if the preference was more accentuated for products produced under environmental dumping. Global demand of crops is prompted via international market that can be appropriately regulated with Multilateral Environmental Agreements (MEA) to balance both trade and nature conservation (UNEP, 2013). Regulated international trade may encourage the sustainability in crop system of exporting countries by paying farmers for ecosystem services they generate (FERRARO and KISS, 2002).

Price adjustment to internalize environmental cost (externalities), for instance, via certification of products, can induce consumers to pay for the conservation output, which may end up increasing the economic viability with the adoption of pollinator friendly practices economically. Certification scheme of pollinator-friendly agricultural is not an easy task (PAGIOLA et al., 2004), because the supervision on farmers can be highly expensive for government, especially in less developed countries. However, this supervision has been made in some developing countries, e.g., the Rural Environmental Registry in Brazil that consists in monitoring conserved areas inside private owned lands via a georeferencing Web system (SOARES-FILHO et al., 2014; Chapter 2).

A Multilateral Environmental Agreement can be focused on some specific crops, in which associated crop systems are more harmful to pollinators or located inside hotspot regions of biodiversity (e.g., cocoa in Ghana, palm oil in Indonesia, coffee in Vietnam, soybean and common bean in Brazil, see CONSERVATION INTERNATIONAL, 2004; TREWEEK et al., 2006; Chapter 1 and 2). An example is the Soy Moratorium in Brazil that is an agreement for zero-deforestation in which major traders agreed to purchase only soy harvested on lands non-deforested (GIBBS et al., 2015). Although such agreement is not directly focused on pollinator protection, the conservation output benefited biodiversity in Amazon region by reducing the participation of soybean in deforestation from 30% to ~1% (RUDORFF et al., 2011; GIBBS et al., 2015).

The transfer of financial resources can help to import or develop new technologies of lower impact on pollinators, similarly to Clean Development Mechanism for carbon sequestration. Such technological solutions involve local intensification of production via the optimized use of ecosystem services, i.e., the ecological intensification (BOMMARCO et al., 2013). Integrated ecosystem services management (e.g., water provision, biocontrol agents, crop pollination, among others) is able to close yield gaps and increase crop supply with no or less expansion in cropland area (BOMMARCO et al., 2013; GARIBALDI et al., 2016a).

Although this study focuses on virtual pollination trade, bee colonies trade (e.g. *Apis mellifera* and *Bombus terrestris*) is an opportunity for businesses to provide pollination services for some farming systems worldwide (e.g. greenhouse production of tomatoes and strawberries) (HOGENDOORN et al., 2000; MALAGODI-BRAGA and KLEINERT, 2004; CUNNINGHAM and FEUVRE, 2013; VELTHUIS and DOORN, 2006). Since 1990, the international market of beehives traded almost 50 thousand of hives with an economic gain of US$ 231 million (FAO, 2018). However, the amount of beehives is not enough to meet the global demand for crop pollination (AIZEN and HARDER, 2009) and is not appropriate for some crop systems (e.g., common bean, CHAPTER 1; GARIBALDI et al., 2013). Moreover, this human-made service only complements the wild pollination (GARIBALDI et al., 2013) and the inclusion of an exotic species via importation of bee hives is dangerous for native pollinators and ecosystems (POTTS et al., 2010). Thus, a regulatory framework is needed to monitor the movement of managed bees between countries (DICKS et al., 2016).

5. Conclusion

Market laws are strong regulators of land use practices worldwide. While the decision of producing a certain product is responsibility of each country, consumers should also assume responsibility for their choices. By evaluating virtual flow of pollination among countries, we demonstrated that developed countries are using a great part of this service, especially from less developed countries. However, intensive management of pollinator-dependent crops to support external demand may be occurring at the cost of natural environment (environmental dumping). Our results highlight the need for a trade policy that motivates the adoption of more pollinator-friendly practices on exporting farm systems, for example, the certification of products or transfer of technologies.

Agricultural production to meet global demand has been considered as a great challenge for food security in exporting countries, because land use for food production competes with national and international demands. Countries with limited capacity to import are more dependent on national production, so their food security may be threatened by exportation associated to ecosystem depletion. The mutually dependence of countries on virtual pollination can help to develop strategies to protect biodiversity by conserving natural areas and managing associated ecosystem services to close yield gaps. Thus, an international coordination can help to implement environmental trade policy to increase the global sustainability.

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Supplementary Material S4

Dataset

https://github.com/lipeconomia/Material-suplementar

Supplementary Material S5

Table 10 – The effect of development level of exporting countries and of their trading partners on virtual pollinator exportation and total exportation. We applied a Box-Cox transformation on virtual pollinator exportation (ƛ=0.1) and on total exportation (ƛ=0.075).

	Virtual pollinator exportation	Overall exportation of crops
R^2	0.05	0.09
Intercept	9.78 (0.73)	35.12 (0.13)
HDI	14.47 (0.70)	-15.92 (0.61)
HDI_exp	19.87 (0.61)	-17.46 (0.59)
HDI*HDI_exp	-9.17 (0.86)	38.66 (0.36)

Source: Elaborated by authors.

Table 11 – Countries' dependence on virtual pollinator importation (DVP) and importation of crops associated to their development level. Countries' dependence on virtual pollinator importation (DVP) was measured by the annually average of the ratio between the importation and domestic consumption of virtual pollinator importing countries over 1993-2015. Countries' dependence on importation of crops was also measured by the annually average of the ratio between importation and consumption of crops in importing countries over 1993-2015. Independent variable was the annually average of Human Development Index (HDI) of importing countries over 1993-2015. The Box-Cox transformation was applied on DVP (ƛ=0.037) and importation of crops (ƛ=0.18) to normalize residuals.

	Dependence on virtual pollinator importation	Dependence on importation of crops
R^2	0.44	0.21
Intercept	-6.36 (0.00)	-3.35 (0.)
HDI	6.07 (0.00)	2.62 (0.00)

Source: Elaborated by authors.

Table 12 – Effect of the difference between the level of development of importing countries and their trading partners on virtual pollinator importation and importation of crops. Response variables were the virtual pollinator importation and importation of crops of countries over 1993-2015. Independent variable was the annually average of the ration between the Human Development Index of importing countries and of their trading partners over 1993-2015 (HDI/HDI_imp). Both response variables were log-transformed to normalize residuals. P-value in parentheses.

	Importation of virtual pollinator	Overall importation of crops
R^2	0.25	0.10
Intercept	7.67 (0.00)	13.41 (0.00)
HDI/HDI_imp	6.88 (0.00)	3.75 (0.00)

Source: Elaborated by authors.

Table 13 – The effect of domestic consumption and exportation on cropland dedicated to pollinator-dependent crops and on overall cropland. Response variable was the variation of cropland with pollinator-dependent crops and with all crops in exporting countries between 2015 and 1993. Independent variables were the variation of domestic consumption and exportation of pollinator-dependent crops ('Consp' and 'Exp') and all crops ('Cons' and 'Ex') between 2015 and 1993, and the development level of the exporting countries (HDI) and of their trading partners (HDI_exp). Response variable and exportation (EX) were log-transformed to normalize residuals. '*' indicates interaction between variables. Domestic consumption (Cons) and exportation (EX) variables were transformed using the standard score in order to compare the magnitude of the effect of both variables on cropland expansion.

	Cropland expansion with Pollinator-dependent crops		Overall cropland expansion
R^2	0.26	R^2	0.31
Intercept	0.76 (0.01)	Intercept	0.11 (0.00)
Consp	0.51 (0.04)	Cons	0.22 (0.00)
Exp	0.27 (0.00)	Ex	0.14 (0.00)
HDI	-0.75 (0.07)	HDI	
HDI_exp		HDI_exp	
Cons*HDI	-0.75 (0.04)	Cons*HDI	
EX*HDI_exp		EX*HDI_exp	

Source: Elaborated by authors.

CONCLUSÃO GERAL

Os resultados desta tese contribuem para as discussões em torno de um dos maiores desafios atuais da sociedade humana: conciliar o aumento da produção agrícola necessária para atender a crescente população humana, com a conservação dos ecossistemas e de seus serviços. Embora o sistema agrícola seja uma ameaça aos ecossistemas, os serviços ecossistêmicos são essenciais para a produção agrícola. Partindo das diversas contribuições das áreas das ciências naturais, este estudo abordou essa problemática por meio de uma visão socioeconômica destacando o fenômeno do declínio dos polinizadores. Os polinizadores aumentam a produtividade e a qualidade dos produtos agrícolas, mas eles estão ameaçados pelo uso intensivo de insumos químicos e pela destruição de habitats naturais decorrentes da expansão dos campos agrícolas. Por isso, a polinização foi um estudo de caso apropriado para demonstrar como é possível equilibrar os interesses econômicos e ecológicos por meio de estratégias de gestão que incorpore os serviços ecossistêmicos como insumos de produção agrícola.

A tese abordou três níveis de análise associados a diferentes tomadores de decisão: nível local (produtor rural), nível da paisagem (formuladores de políticas públicas), nível nacional/global (países) (Fig. 25). Essa divisão adotada neste trabalho permitiu compreender que cada tomador de decisão possui um papel crucial na proteção aos polinizadores, porém a sua capacidade de atuação está limitada ao seu nível de atuação. Por exemplo, os produtores rurais conseguem atuar mais diretamente no manejo agrícola reduzindo os insumos químicos ou conservando/restaurando as áreas de vegetação nativa. Já os formadores de políticas públicas definem leis ambientais que abrangem todo o setor agrícola inserido em sua jurisdição (i.e., políticas municipais, estaduais, nacionais e internacionais). Dessa forma, o estudo permitiu concluir que a efetividade de uma estratégia de proteção aos polinizadores necessidade, primeiramente, compreender a capacidade de atuação de tais agentes.

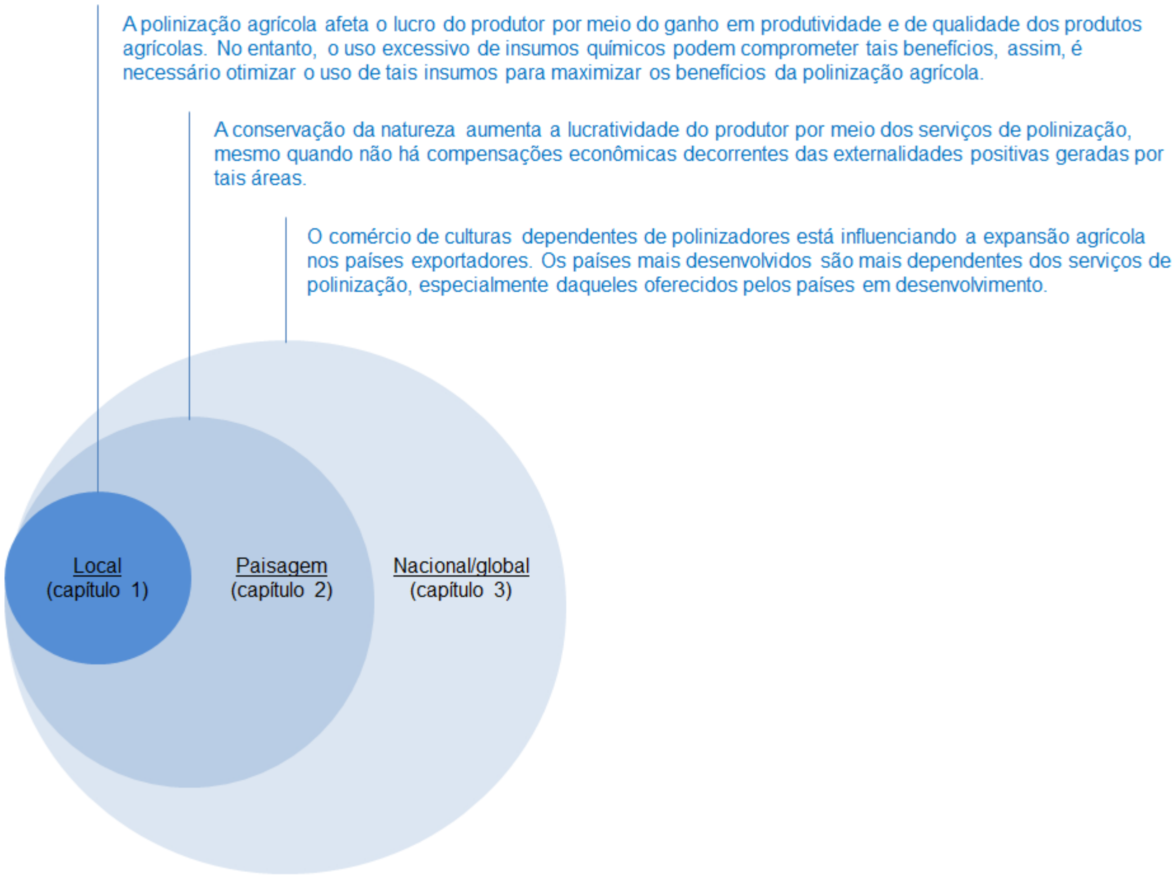

FIG. 25 - Mapa da tese com as principais contribuições associadas a cada nível de análise.

Fonte: Elaborado pelo autor.

A polinização agrícola também beneficia a formação de renda do produtor. Nesse sentido, o estudo mostrou que, apesar das ações de conservação apresentar custos associados, os benefícios com o serviço ecossistêmico de polinização podem ser compensatórios. Para isso, é necessário avaliar tais benefícios e o modelo proposto no primeiro capítulo pode ser uma ferramenta para orientar futuros estudos e decisões de gestores agrícolas. Vale destacar que os custos associados ao manejo de polinizadores se referem tanto a gastos explícitos (e.g., implantação de colmeias de abelhas, restauração de vegetação nativa, entre outros) quando gastos implícitos, denominados custo de oportunidade (i.e., potencial ganho econômico com a exploração agrícola de áreas naturais conservadas). Considerando existe uma elevada complexidade em cada sistema agrícola, é esperado que nem sempre os benefícios da polinização selvagem compensem tais custos. Nesse sentido, a tese também conclui que é necessário considerar possíveis mecanismos de compensação para aumentar a atratividade das ações de conservação.

O estudo analisou os efeitos de um mecanismo de pagamento ao produtor que conserve um percentual de área natural superior ao valor definido pela legislação ambiental (Princípio da Adicionalidade). Essa discussão também permite destacar outro aspecto da multifuncionalidade da agricultura, onde o agricultor oferta tanto os produtos agrícolas quanto os serviços ecossistêmico. Além de proteger os polinizadores, tais áreas também estimulam a oferta dos serviços de polinização e de outros serviços ecossistêmicos que beneficiam os produtores da vizinhança e a sociedade como um todo. Dessa forma, a formulação de políticas de polinizadores também precisa considerar a existência de tais externalidades positivas. No caso do feijão, o estudo apontou que mesmo considerando tais mecanismos de pagamento, os benefícios com a polinização agrícola representam grande parte do lucro do produtor. No entanto, para os casos em que não ocorra viabilidade exclusivamente com tais serviços, a internalização das externalidades positivas tem um papel fundamental na transferência dos custos da conservação para aqueles produtores que não protegem o meio ambiente, ou seja, para aqueles que conservam um percentual de áreas naturais abaixo do valor definido pela legislação ambiental. Além disso, a tese sugere que a regulação desse fluxo de pagamento é um papel importante para o poder público, pois somente ele pode definir mecanismos coercitivos.

Medidas econômicas baseadas no pagamento dos serviços ecossistêmicos poderão beneficiar principalmente os pequenos produtores. Além disso, a produção em pequena escala, geralmente, utiliza menos insumos químicos e aumenta a diversidade na paisagem rural. Com isso, eles são importantes produtores de alimentos que são dependentes de polinizadores, contribuindo, assim, para a segurança alimentar. Futuras pesquisas poderão compreender como a gestão de polinizadores pode beneficiar a formação de renda do pequeno produtor mediante o aumento da produção agrícola e com a produção de mel com as abelhas manejadas. Dessa forma, a união de pequena produção com o manejo de polinização agrícola pode ser uma excelente orientação para futuras políticas que busquem conciliar as demandas econômicas com o equilíbrio ecológico.

Este estudo multi-nível permitiu ampliar a compreensão dos efeitos da polinização, que ocorre ao nível local da propriedade rural, para níveis elevados de análises (nacional/global). A governança ambiental global referente aos polinizadores esteve baseada no que cada país poderia fazer em termos de proteção da sua biodiversidade e na regulação do uso e do comércio de abelhas e de pesticidas. Este estudo demonstrou que essas ações podem ir além, porque existem diversas outras práticas amigáveis aos polinizadores que necessitam de apoio para serem implantadas, tanto em regiões agrícolas de baixa renda como em regiões com grandes do agronegócio. Com a abordagem no nível nacional/global e com o uso do conceito de fluxo virtual de polinização, foi possível compreender como a polinização associada ao nível de desenvolvimento dos países influencia o mercado internacional. Além disso, um importante resultado proveniente dessa análise foi que a exportação é um dos grandes fatores de expansão de áreas agrícolas dedicadas às culturas dependentes de polinizadores. Mesmo que um país esteja aplicando leis rígidas no âmbito da produção, tais como o controle no uso de pesticidas ou na conservação da natureza, o seu consumo poderá ter um grande impacto em outros países que estejam explorando seus ecossistemas para produzir commodities de exportação. Isso mostra que, no que tange uma estratégia global de proteção aos polinizadores, existe uma relação de responsabilidade compartilhada entre os países produtores e consumidores dos produtos dependentes de polinização. A identificação nichos de mercados em que ocorra um acentuado impacto ambiental pode ser um primeiro passo para traçar estratégias de regulação e governança ambiental global. Tais mecanismos envolvem desde a certificação de produtos específicos produzidos a partir de práticas amigáveis aos polinizadores até a transferência de tecnologias e recursos entre países ricos e pobres.

Historicamente, o processo de crescimento econômico de um país foi fortemente baseado na exploração intensa dos recursos naturais. Os países mais pobres buscam na agricultura uma oportunidade de se desenvolver, mas a trajetória não precisa ser baseada no esgotamento dos recursos naturais. Por isso, tais opções descritas acima poderão guiar as novas trajetórias de desenvolvimento pautadas na sustentabilidade.

Com base em todos os resultados, conclui-se que a proteção dos polinizadores depende de uma coordenação de ações entre tomadores de decisões que atuam em diversos níveis onde os impactos do declínio de polinizadores são percebidos. Tais ações incluem a adoção de práticas amigáveis aos polinizadores na escala da propriedade rural pelos produtores, de modo a não comprometer a lucratividade dos sistemas agrícolas. A viabilidade de tais práticas pode ser estimulada por meio de políticas ambientais que utilizam instrumentos econômicos. Essas políticas também podem estar articuladas com outros países para que seja incentivada também a adoção de tais ações amigáveis aos polinizadores nos sistemas agrícolas de exportação. Por fim, a proteção dos polinizadores e o uso sustentável de seus serviços são cruciais para a sustentabilidade na agricultura.

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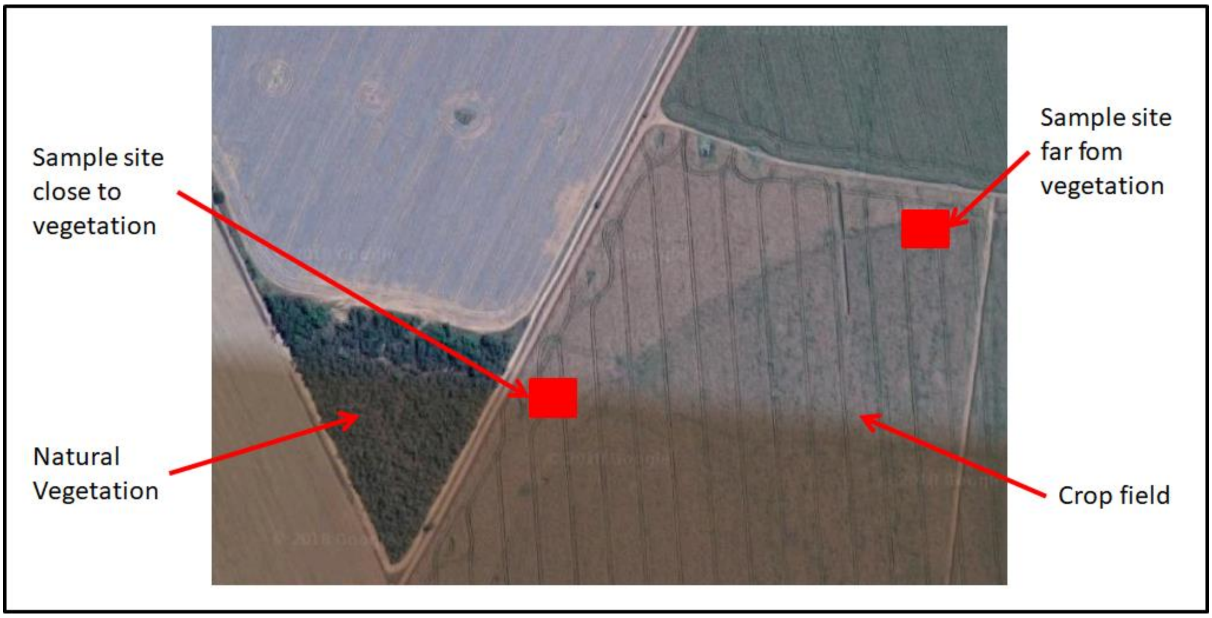
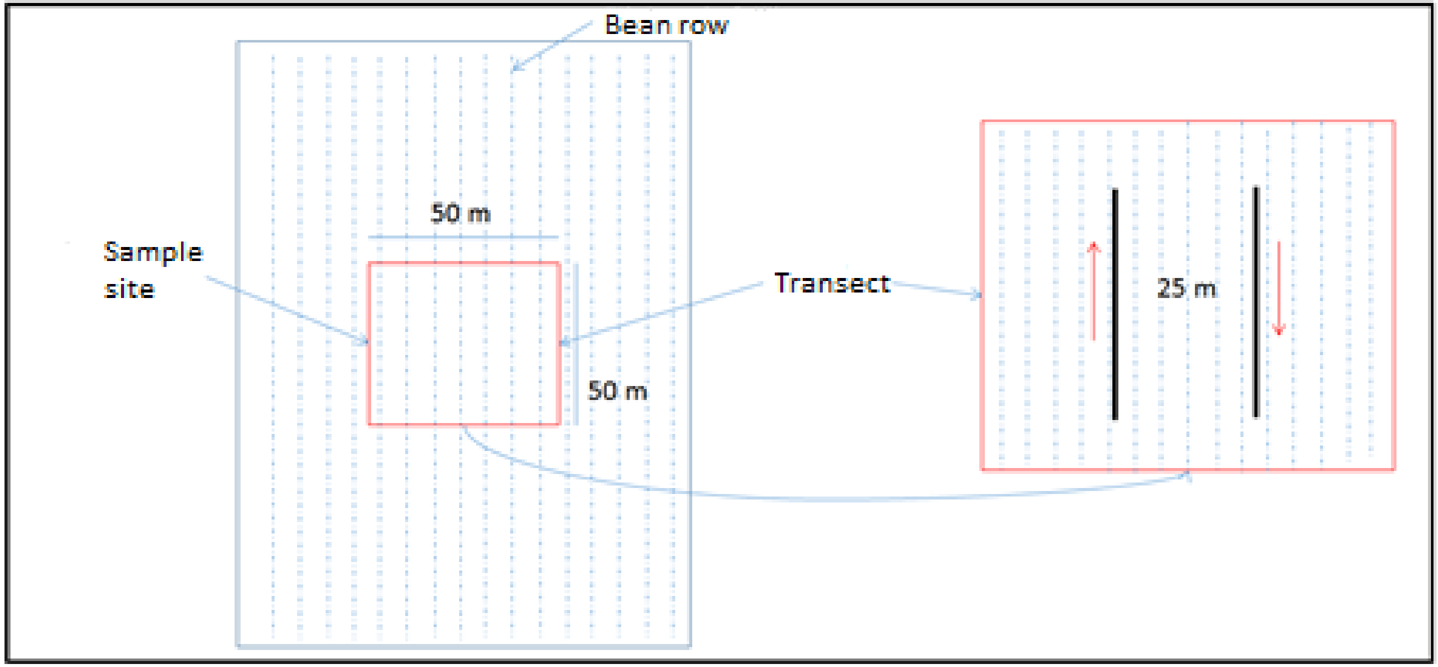
Apêndice A – Esquemas e fichas para a coleta dos dados de campo



Exemplo de um local de amostragem. O capital natural está representado como “Natural vegetation”.



Esquema do local de amostragem da polinização agrícola. O quadrado vermelho representa o local de amostragem onde dois transectos foram definidos (linhas pretas). Cada transecto representa uma área de 1x25m.

Ficha de coleta de dados de polinização

DADOS DE POLINIZAÇÃO					
Produtor:	Campo:	Ponto amostral:	Tratamento com penergetic: ( ) Sim ( ) Não	Data:	Horário:

N° de flores abertas observadas:	Observador:	Proximidade de árvores (m):	Coordenadas:
% de nuvens:	Vento:	Temperatura (°C):	Humidade:

Tipo de visitante	Visita						Capturas	Descrição dos visitantes (morfotipo; comportamento)
	Feijão	Pilhadores (Feijão)	Extras	Sp1	Sp2	Sp3		
Apis mellifera								
Outras abelhas								
Syrphidae								
Outros díptera								
Lepidotera								
Coleoptera								
Outros visitantes								
Grupo não identificado								

Observações:

Ficha de registro de dados de produção

Produtor:	Ponto amostral:	DATAS				Tratamento:
		Coleta no campo	Separação das sementes	Secagem	Pesagem	( ) Transecto ( ) Ensacado ( ) Não ensacado

Plantas	Informações da vagem											Informações do feijão				
	qtde	Com furo	não produziu feijão	Vagens com feijão germinando	Tamanho vagem 1	Tamanho vagem 2	Tamanho vagem 3	Feijão fertilizado	Feijão não fertilizado	Feijão predado	Feijão com fungo	Feijões			Qtde feijão	Peso feijão
												Germ.	Pred.	Fungo		
1																
2																
3																
4																
5																
6																
7																
8																
9																
10																
11																
12																
13																
14																
15																
Observações:																

Anexo A: Crop fertilization affects pollination service provision – Common bean as a case study