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ECONOMIC VALUATION AND VULNERABILITY OF THE POLLINATION ECOSYSTEM SERVICE AND NUTRITIONAL COMPONENTS OF POLLINATOR DEPENDENT AND NON-DEPENDENT CROPS

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Tese apresentada ao Programa de Pós-Graduação em Biologia Vegetal da Universidade Federal de Pernambuco como parte dos requisitos necessários à obtenção do título de doutora em Biologia Vegetal.

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Orientadora: Profª Drª Ariadna Valentina Lopes
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RESUMO

Os serviços ecossistêmicos são o conjunto de diversas funções ecológicas essenciais ao bem-estar humano. Neste contexto, essa tese está estruturada, em três capítulos que buscam identificar como o serviço de polinização e seus benefícios econômicos estão sendo globalmente mensurados e publicados; calculam o valor econômico da polinização na agricultura brasileira, quais fatores influenciam esse valor, além de identificar áreas de maior vulnerabilidade ao declínio de polinizadores animais; e no terceiro capitulo tratamos da contribuição nutricional dos polinizadores á dieta humana, através da comparação entre composição e concentração de nutrientes em culturas dependentes não dependentes de polinizadores. No primeiro capítulo examinamos como a avaliação econômica dos serviços de polinização de culturas foi investigada na literatura e analisamos as estimativas dos valores monetários dos serviços de polinização agrícola, bem como os investimentos (financiamento/subsídios à pesquisa) e ações políticas associadas a polinizadores e polinização. Documentamos um aumento no número de estudos de avaliação econômica de serviços de polinização nas últimas duas décadas, com um crescimento substancial nos últimos cinco anos. Enfatizamos que há uma acentuada falta de dados sobre culturas comerciais importantes, principalmente nos países em desenvolvimento. Demonstramos e atualizamos os valores globais estimados do serviço de polinização agrícola, mostrando uma tendência crescente ao longo do tempo nos valores das estimativas de serviço de polinização, embora as estimativas para culturas específicas sejam amplamente variáveis nas escalas local e regional. Embora a avaliação dos serviços de polinização e a economia e a política associadas continuem sendo áreas embrionárias de pesquisa, a polinização mediada por animais é claramente um serviço ambiental de alto valor, que fortalece bastante os argumentos de conservação em todo o mundo. No segundo capítulo tentamos acessar a importância dos polinizadores na produção de frutas e, consequentemente, o ganho econômico de produções para diversas culturas frutíferas em escala local e regional em todo o domínio da floresta atlântica Brasileira. Através de uma abordagem bioeconômica, descobrimos que a polinização tem uma contribuição muito grande para a produção de commodities de frutas, mas também é um serviço ecossistêmico essencial e vulnerável em muitos municípios ao norte do país. No terceiro capítulo utilizamos dados de nutrientes das principais culturas brasileiras para investigar como os componentes nutricionais estão presentes em culturas dependentes e não dependentes de polinizadores. Este estudo fornece a primeira avaliação dos conteúdos de frutos e sementes relacionados a culturas dependentes e não dependentes de polinizadores, que incluem o conteúdo de água e o fornecimento de energia. Culturas dependentes da polinização animal exibem alto teor de água e representam uma fonte relevante de lipídios, vitamina A, vitamina B, vitamina B2 (riboflavina), vitamina B9 (folato), vitamina C e vitamina E. Portanto, a diminuição dos polinizadores pode impactar drasticamente a dieta humana, a saúde e a segurança alimentar. Esperamos dar um passo adiante no incentivo a práticas agrícolas mais sustentáveis e amigáveis aos polinizadores geram benéficos para todas as partes, incluindo benefícios econômicos e para o bem-estar humano através da saúde e segurança alimentar.

Palavras-Chaves: Polinização animal. Segurança alimentar. Valoração econômica.
nutrientes. Vulnerabilidade.

ABSTRACT

Ecosystem services are the set of diverse ecological functions essential to human well-being. In this context, this thesis is structured in three chapters that seek to identify how the pollination service and its economic benefits are being globally measured and published; calculate the economic value of pollination in Brazilian agriculture, which factors influence this value, in addition to identifying areas of greatest vulnerability to the decline of animal pollinators; and in the third chapter we deal with the nutritional contribution of pollinators to the human diet, by comparing composition and concentration of nutrients in dependent cultures that are not dependent on pollinators. In the first chapter we examine how the economic evaluation of crop pollination services has been investigated the literature and we analyze the estimates of the monetary values of agricultural pollination services, as well as investments (research funding / subsidies) and policy actions associated with pollinators and pollination. We have documented an increase in the number of studies on the economic assessment of pollination services in the past two decades, with substantial growth in the past five years. We emphasize that there is a marked lack of data on important commercial crops, especially in developing countries. We demonstrate and update the estimated global values of the agricultural pollination service, showing an increasing trend over time in the values of the pollination service estimates, although the estimates for specific crops vary widely at the local and regional scales. Although the assessment of pollination services and the associated economy and policy remain embryonic areas of research, animal-mediated pollination is clearly a high-value environmental service that greatly strengthens conservation arguments around the world. In the second chapter we try to access the importance of pollinators in fruit production and, consequently, the economic gain of productions for different fruit crops on a local and regional scale throughout the Brazilian Atlantic Forest domain. Pollination has a very large contribution to the production of fruit commodities, but it is also an essential and vulnerable ecosystem service in many municipalities in the north of the country. On a landscape scale, the economic value of the pollination service for agricultural production appears to be affected by changes in land use, such as deforestation, remaining forest cover and urban expansion. In the third chapter we use nutrient data from the main Brazilian cultures to investigate how the nutritional components are present in dependent and non-dependent pollinator cultures. This study provides the first assessment of fruit and seed content related to dependent and non-dependent pollinator crops, which include water content and energy supply. Crops dependent on animal pollination exhibit high water content and represent a relevant source of lipids, vitamin A, vitamin B, vitamin B2 (riboflavin), vitamin B9 (folate), vitamin C and vitamin E. Therefore, the decrease pollinators can drastically impact the human diet, health and food security. We hope to take a step further encouraging more sustainable and pollinator-friendly agricultural practices is beneficial to all parties, including economic benefits and human well-being through health and food security.

Keywords: Animal pollination. Food security. Economic valuation. Nutrients. Vulnerability.

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1 INTRODUÇÃO

Os serviços ecossistêmicos são o conjunto de diversas funções ecológicas essenciais ao bem-estar humano. Esses serviços podem fornecer benefícios significativos e mensuráveis à humanidade, fornecendo argumentos para a conservação do ecossistema e biodiversidade. A polinização animal compreende um importante serviço ecossistêmico, uma vez que a reprodução e a produtividade de muitas flores silvestres e plantas cultivadas dependem fortemente, enquanto outras se beneficiam da visita de polinizadores animais. Este serviço tem se mostrado negativamente relacionado a alterações de habitats naturais, tais como perda de habitat, intensificação do uso da terra e isolamento de habitat, mudanças climáticas, entre outras.

Declínios a longo prazo nas populações de polinizadores e ameaças relacionadas à reprodução das plantas levaram à preocupação de uma perda generalizada de serviços de polinização. Embora os declínios dos polinizadores e seus impactos na agricultura e nos ecossistemas naturais tenham recebido grande atenção em países desenvolvidos, como na Europa e na América do Norte, essas questões são muito menos estudadas nos países em desenvolvimento. No entanto, há razões para acreditar que as consequências do declínio dos polinizadores podem ser ainda mais agravantes e prejudiciais para as economias, ecossistemas e comunidades em países em desenvolvimento como o Brasil.

Neste contexto, essa tese está estruturada, em três capítulos que buscam identificar como o serviço de polinização e seus benefícios econômicos estão sendo globalmente mensurados e publicados; calculam o valor econômico da polinização na agricultura brasileira, quais fatores influenciam esse valor, além de identificar áreas de maior vulnerabilidade ao declínio de polinizadores animais; e no terceiro capitulo tratamos da contribuição nutricional dos polinizadores á dieta humana, através da comparação entre composição e concentração de nutrientes em culturas dependentes não dependentes de polinizadores.

No primeiro capítulo, intitulado “Pollination ecosystem service: a comprehensive review of the economic value, research funding and policy actions” utilizamos a cientometria como principal ferramenta, com o objetivo de analisar como a valoração econômica do serviço de polinização tem sido investigada e publicada na literatura científica, além de revisar os valores econômicos estimados para o serviço de polinização das culturas globalmente. Observamos que desde a década de 1990 tem havido uma tendência crescente de publicações estimando e discutindo os valores econômicos da polinização. Os valores mundiais estimados para serviço de polinização variam de US$ 20 a US$ 340 bilhões devido a muitos fatores, discutidos no decorrer do manuscrito. Embora os métodos sejam cada vez mais sofisticados, os estudos geralmente não conseguem propor metodologias que possam ser facilmente replicadas a diversas localidades e culturas, dificultando a comparação entre os valores e os status de dependência e vulnerabilidade da produção agrícola ao serviço de polinização.

O segundo capítulo com título “Economic value of fruit crops and vulnerability of the production in face of a possible pollinator decline in the Brazilian Atlantic forest domain” tem como objetivo avaliar a dependência das principais culturas frutíferas no Brasil, estimar o valor econômico do serviço de polinização para essas culturas e quais fatores influenciam esse valor, além de avaliar quais áreas são mais vulneráveis ao declínio dos polinizadores. Para estimar os benefícios econômicos da polinização, buscamos uma abordagem bio-econômica, utilizando dados da biologia reprodutiva e produção agrícola de 29 culturas frutíferas. Vimos que 43,2% das culturas frutíferas são essencialmente ou altamente dependentes de polinização animal e outras 46,6%, de alguma forma, se beneficiam da polinização. O serviço de polinização contribui para a agricultura brasileira em mais de US$ 1.75 bilhões e grande parte desse valor é devido ao valor da produção e à quantidade produzida para exportação de commodities como café, cacao e laranja. Em nossa análise espacial (SIG), áreas de vulnerabilidade da produção agrícola ao declínio de polinizadores estão distribuídas por toda a área amostrada, devido à grande produção de culturas dependentes de polinizadores em diversos municípios do Brasil. Entretanto, esses hotspots de vulnerabilidade também podem ser interpretados como áreas potencialmente indicadas para a intensificação ecológica da agricultura, com práticas amigáveis aos polinizadores, que poderia elevar a quantidade, qualidade e, consequentemente, o valor da produção das culturas.

No terceiro capítulo intitulado “Pollinator dependent crops accounts for a substantial portion of most nutritional components when compared to non-dependent crops”, tratamos de um benefício do serviço ecossistêmico de polinização que ainda tem sido pouco explorado na literatura. Nesse capítulo, avaliamos ocorrência e concentração de nutrientes nas 40 principais culturas agrícolas produzidas no Brasil, comparando o conteúdo nutricional entre as culturas dependentes e não dependentes de polinização. Testamos se existe um agrupamento de nutrientes que estão diretamente ligados a culturas dependentes de polinizadores e as concentrações dos componentes nutricionais nas culturas dependentes e não dependentes. Nossos resultados sugerem que 57% da variação nutricional entre as culturas dependentes e não dependentes de polinizadores está relacionada ao conteúdo de água, energia, macronutrientes, vitaminas e minerais. Observamos que frutos e sementes de plantas de dependentes exibem alta concentração de água e compartilham uma concentração alta de lipídios, vitamina A, vitamina B1, vitamina B2 (riboflavina), vitamina B9 (folato), vitamina C e vitamina E (β-tocoferol). Estas diferenças entre o conteúdo nutricional das culturas dependentes e não dependentes indicam que os serviços de polinização podem ser relevantes para atender às necessidades da dieta humana. Com esses resultados, nós ressaltamos a importância do serviço de polinização na alimentação humana, saúde e a segurança alimentar no Brasil e em outros países que importam commodities brasileiras.

A agricultura brasileira é fortemente dependente do serviço de polinização animal e, preocupantemente, esse serviço vem sendo ameaçado pela degradação de habitats naturais, uso intensivo de pesticidas e mudanças climáticas. Como a avaliação dos serviços ecossistêmicos é uma ferramenta chave para facilitar o desenvolvimento de estratégias e gestão para conservação de recursos naturais, esse estudo fornece elementos importantes para decisões políticas e de interesse para toda a sociedade. Além disso, contribui com informações importantes sobre um tema atual e mundialmente discutido.

2 FUNDAMENTAÇÃO TEÓRICA

2.1 SERVIÇO ECOSSISTÊMICO DE POLINIZAÇÃO

Os serviços ecossistêmicos, também chamados de *benefícios da natureza para as pessoas*, referem-se a todos os benefícios que a humanidade obtém da natureza (Potts *et al.*, 2016). O conceito de serviços ecossistêmicos foi originalmente concebido como uma metáfora para refletir a dependência da sociedade em relação aos ecossistemas (Gomez-Baggethun and Ruiz-Pérez, 2011). Esta abordagem permite destacar o papel fundamental do ecossistema e da biodiversidade na manutenção da vida, bem-estar humano e sustentabilidade econômica a longo prazo (Jax *et al.*, 2013).

Com base no *Millennium Ecosystem Assessment* (2003), os seguintes três tipos de categorias de serviços ecossistêmicos foram definidos: (i) serviços de produção; (ii) serviços de regulação; e (iii) serviços culturais. Serviços de polinização têm sido considerados serviços de regulação, assim como controle de pragas e fixação de nitrogênio, mas pode igualmente ser considerado como um serviço de produção.

A posição dos serviços ecossistêmicos na interface ciência-sociedade proporciona o diálogo entre disciplinas acadêmicas e auxilia a comunicação entre os diferentes grupos de interesse como conservacionistas, agricultores, economistas, políticos e empresários (Jax *et al.*, 2013). A partir da década de 1980 surgiram esforços para estimar o valor dos serviços ecossistêmicos (VSE) de polinização, principalmente justificados por iniciativas internacionais de conservação (Gomez-Baggethun and Ruiz-Pérez 2011), A expansão dessa abordagem além dos círculos acadêmicos especializados ocorreu na década de 1990. O ponto crítico para essa mudança, da teoria à política, ocorreu através do endosso parcial da abordagem de serviços de ecossistema pela Convenção sobre a Diversidade Biológica, em 1992. Na década seguinte, foram publicados os primeiros trabalhos com o desenvolvimento de estruturas e métodos para a identificação, classificação e valoração de serviços ecossistêmicos (Daily 1997; Costanza *et al.*, 1997; de Groot *et al.*, 2010).

Posteriormente à publicação da Avaliação Ecossistêmica do Milênio em 2005 (MMA, 2005), os serviços dos ecossistemas se estabeleceram na agenda política ambiental internacional. Em 2012 foi criada a Plataforma Intergovernamental das Nações Unidas sobre Biodiversidade e Serviços dos Ecossistemas (IPBES, sigla em inglês), instituição que age como interface entre a comunidade e os responsáveis científicos, visando construção e fortalecimento do uso da ciência na formulação de políticas em relação aos serviços dos ecossistemas e da biodiversidade. Em 2016, contando com a colaboração de 77 especialistas, esses esforços culminaram com a publicação do relatório intitulado "Avaliação Temática de Polinizadores, Polinização e Produção de Alimentos" (Potts *et al*., 2016). Segundo o relatório, 35% das lavouras mundiais dependem de polinização animal e mais de três quartos das principais lavouras alimentícias no mundo dependem, em algum grau, dos serviços de polinização animal, seja para garantir o volume ou a qualidade da produção. Atualmente, entre 5% e 8% da produção agrícola anual global está diretamente ligada à polinização animal, o que corresponde a um mercado que varia entre US$ 235 bilhões e US$ 577 bilhões. No Brasil, a riqueza gerada com auxílio dos polinizadores foi estimada em torno de US$ 12 bilhões.

Estudos recentes constatam que é possível conciliar agricultura com conservação da biodiversidade e ter como resultado o aumento da produtividade agrícola. Por exemplo, Garibaldi *et al.* (2016a) avaliou o número de polinizadores, a biodiversidade e o rendimento de 33 cultivos dependentes de polinizadores em 12 países e observou que o que mais contribuiu para a diferença entre as taxas de produção foi o aumento na densidade de polinizadores, que se equiparou ao incremento de técnicas convencionais de intensificação agrícola, como o uso de fertilizantes sintéticos e monoculturas. Abordagens como a de Garibaldi *et al.* (2016), além de outros estudos e iniciativas (ex. A Iniciativa Brasileira de Polinizadores (IBP), Iniciativa Internacional de Polinizadores (IPI), Projeto Polinizadores do Brasil, coordenado pelo Ministério do Meio Ambiente) geram subsídios para mudanças à novo paradigma da sustentabilidade, por meio da intensificação ecológica da agricultura.

A partir desses novos indícios, espera-se que a conservação de polinizadores seja encorajada, superando, assim, a oposição tradicional entre economia e conservação (Armsworth *et al*., 2007). Em outras palavras, demonstrando o valor dos serviços de polinizadores, agricultores, tomadores de decisão e público em geral serão motivados a implementarem práticas que gerem proteção aos habitats de polinizadores, impulsionando a implementação de programas agroecológicos com foco em polinizadores e, consequentemente, gerando contribuições à conservação de maneira geral (Winfree *et al*., 2011).

2.2 POLINIZAÇÃO E PRODUÇÃO DE FRUTIFERAS

Nas últimas décadas, estudos têm apresentado a importância da polinização por insetos como um serviço ecossistêmico para produção agrícola (e.g. Gallai *et al.* 2008; Winfree *et al.* 2011; Leonhardt *et al.* 2013; Gallai *et al.* 2015). No geral, a produção agrícola depende direta ou indiretamente de plantas que necessitam de polinização animal (Aizen *et al*., 2008; Klein *et al*., 2007; Kremen *et al.*, 2007). Diversas culturas consumidas globalmente e com maior volume de produção (e.g. arroz e trigo) são polinizadas pelo vento, entretanto, uma grande proporção de culturas de alto valor nutricional como frutos, sementes, nozes e legumes, são dependentes de polinizadores (Eilers *et al*., 2011). Além disso, os polinizadores melhoram a qualidade dos frutos e, consequentemente, o valor econômico da produção agrícola (Garratt *et al*., 2014; Klatt *et al*., 2014).

Por exemplo, foi analisada a biodiversidade de polinizadores como forma de aumentar a produtividade agrícola em alguns cultivos (Garibaldi *et al*. 2016). Dentre estes, destaca-se a Maçã (*Malus domestica* Borkh), que obteve aumento de 67% na produção de sementes e 44 % na produção de frutos, devido à introdução de uma abelha polinizadora. Em propriedades pequenas, a redução do déficit de polinizadores com aumento na produtividade pode ser alcançada com o aumento da quantidade de polinizadores visitando as flores (densidade). Já nas grandes propriedades, aumentar a diversidade de espécies de polinizadores nos cultivos trazem melhores resultados à produção (Garibaldi *et al*. 2016).

De acordo com o Ministério da Agricultura, o Brasil é o terceiro maior produtor mundial de frutas, e é responsável por 5,7% do volume colhido, com uma produção de 41,5 milhões de toneladas. A base agrícola da cadeia produtiva das frutas abrange 3,0 milhões de hectares e gera 6,0 milhões de empregos diretos. A presença brasileira no mercado externo, com a oferta de frutas tropicais e de clima temperado durante boa parte do ano, é possível pela extensão territorial do país, posição geográfica e condições de clima e solo privilegiadas (MAPA, 2016).

Garantir a segurança alimentar é um dos grandes desafios das próximas décadas. Segundo a FAO (2008), devido às mudanças climáticas e sua influência na produtividade da agricultura, degradação pelo uso extensivo do solo e o crescimento populacional, será necessário aumento da produção agrícola em pelo menos 70% até 2050. Como já vem sendo demostrado em diversos estudos a conservação da biodiversidade e o incentivo a práticas agrícolas mais sustentáveis (Hipólito *et al*., 2018; Kremen *et al*., 2012), através da intensificação ecológica da agricultura (Kovács-Hostyánski *et al*., 2017; Lichtenberg *et al*., 2017), geram cenários win-win, com benefícios para o bem-estar humano que incluem melhores rendimentos econômicos, maior e melhor oferta de alimentos (Potts *et al*., 2016; Garibaldi *et al.*, 2016a).

2.3 METODOLOGIAS DE VALORAÇÃO DO SERVIÇO DE POLINIZAÇÃO

Diversas metodologias têm sido usadas para estimar o valor (monetário ou não) da polinização agrícola. A principal delas, é a abordagem *bioeconômica,* que tem como base a dependência de polinizadores em cada cultura e a sua produção anual (Gallai and Vaissière 2009), utilizando metodologia proposta por Klein *et al*. (2007). Como a polinização é um dos fatores da produção agrícola, variando de acordo com a dependência do polinizador animal, essa abordagem tem sido o método de valoração mais indicado e utilizado recentemente (Hein, 2009).

O método do custo de substituição tem sido usado em estudos recentes (Allsopp *et al*., 2008; Breeze *et al*., 2015), onde o serviço de polinização é avaliado baseado nas taxas de aluguel e no manejo de caixas de abelhas, introduzidas nas áreas de cultivo. Através desse método, foi estimado um valor de polinização agrícola em cerca de US$350 milhões/ano, somente nos Estados Unidos (Burgett *et al*., 2004). Entretanto, esse método falha ao ignorar os custos de produção e manutenção dos apicultores.

O método dos custos evitados (MCE) é aplicado em estudos que medem os possíveis gastos decorrentes da falta dos serviços ambientais (Ortiz 2003). Em outras palavras, o agricultor, ao fazer uso do serviço de polinização, evita incorrer em custos com pagamentos de salários a trabalhadores contratados, que realizariam o trabalho de polinização manual (Vieira and Cruz, 2010). Portanto, o salário de um trabalhador é usado como “proxy” do valor do serviço de polinização manual. Utilizando esse enfoque, (Almeida, 2015) estimaram o custo da polinização manual por trabalhadores em culturas frutíferas no Centro de Endemismo Pernambuco (CEP), região biogeográfica da floresta atlântica (Ribeiro *et al*., 2009). Esse estudo cria uma fórmula que conta com variáveis ligadas à biologia reprodutiva das plantas e às normas trabalhistas no Brasil. O valor anual da polinização por hectare por trabalhador no CEP variou entre R$ 6.218,10 para a goiaba (*Psidium guajava* L.) e R$ 213,19 para a graviola.

Como a valoração dos serviços ambientais é usada para apoiar tomadas de decisão, um foco exclusivamente em valores monetários e de mercado pode negligenciar os impactos de tais decisões sobre outras partes interessadas (Breeze *et al*., 2015). Classificada como preferência declarada, essa metodologia cria um mercado hipotético para bens/serviços ambientais, utilizando um questionário com preferências por pacotes de bens/serviços, estimando a disposição dos entrevistados em pagar para mantê-los conservados ou aceitar uma compensação pela sua degradação (Bateman *et al.*, 2009).

Tais pesquisas de opinião têm sido usadas para avaliar uma gama de serviços ecossistêmicos, tais como a qualidade da água (Zander and Straton, 2010) e sequestro de carbono (MacKeron *et al*., 2009). Segundo Breeze *et al*. (2015) o público em geral considera o conceito ecológico de polinização difícil de ser assimilado e atribuído um valor. No entanto, se cuidadosamente desenvolvidas, metodologias como essa, podem ser usadas para capturar os aspectos benéficos (estético, recreacional, etc) dos serviços ecossistêmicos que não estão incluídos nas tradicionais valorações monetárias.

2.4 JUSTIFICATIVA E RELEVÂNCIA CIENTÍFICA

O serviço de polinização fornecido pela natureza sempre ocorreu sem nenhum custo ou necessidade de interferência das comunidades humanas. Como os campos agrícolas tornaram-se maiores e o uso de produtos químicos agrícolas aumentou consideravelmente a partir da década de 1960, houve uma queda intensa no tamanho e número das populações de polinizadores nas paisagens agrícolas (Gallai and Vaissière 2009) associada com queda na qualidade do serviço de polinização. Apesar de suas inúmeras realizações em termos de proteção de espécies e habitats raros, as abordagens tradicionais de conservação têm sido impotentes para reverter ou estabilizar as crescentes demandas sobre os estoques de capital natural, serviços ecossistêmicos e a biodiversidade (Guo *et al*., 2010; Krausmann *et al*., 2009).

A abordagem conservacionista de áreas naturais sob proteção (i. e. APA, parques, reservas, etc - *fortress conservation*), incorporadas em uma matriz ecologicamente insustentável, reflete a posição dominante ontológica de culturas ocidentais que concebe o ser humano como sendo separado do meio ambiente e conservação da natureza como uma concessão do desenvolvimento econômico (Gomez-Baggethun and Ruiz-Pérez, 2011). Neste contexto, a abordagem de serviços ecossistêmicos oferece uma oportunidade para se afastar da lógica da "conservação contra o desenvolvimento" no sentido de uma lógica de "conservação para o desenvolvimento" (Von Heland and Folke, 2014). Além disso, tem potencial para antecipar possíveis consequências do declínio dos polinizadores para a produção de alimentos e a segurança alimentar (Gallai and Vaissière, 2009; Winfree *et al*., 2011), ilustrando como a gestão adequada dos serviços de polinização e a intensificação ecológica na agricultura, podem reduzir os riscos da produção e aumentar a produtividade (Garibaldi *et al*., 2016a).

Uma vez quantificados economicamente, os valores da polinização, podem ser incluídos como parte das análises de custo-benefício da produção de alimentos, auxiliando produtores e na formulação de políticas públicas para a conservação ecológica, inclusive em paisagens agrícolas (Hanley et al., 2015). Além de indicar contextos nos quais o incentivo e recursos podem ser alocados com maior custo benefício, tanto economicamente, quanto ecologicamente.

Os caminhos futuros para investigação acerca dos serviços ecossistêmicos são a integração, com maior eficácia, entre pesquisa e política através da realização de estudos que combinam valoração dos serviços ambientais, suas nuances e o impacto em um contexto histórico, econômico e social (FAO, 2008).

POLLINATION ECOSYSTEM SERVICES: A COMPREHENSIVE REVIEW OF ECONOMIC VALUES, RESEARCH FUNDING AND POLICY ACTIONS

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Running Page Title: Pollination services: economic valuation and policies

Abstract

Economic valuation of crop pollination services, including potential monetary losses in agricultural production induced by insufficient pollination, is a strategy to quantify the impacts of this critical ecosystem service on food production, food security and the global economy, and to drive policy actions. We examined how the economic valuation of crop pollination services has been investigated across the ecological and economics literature and review estimates of monetary values of crop pollination services, as well as the investments (research funding/grants) and policy actions associated with pollinators and pollination. We documented an increase in the number of economic valuation studies on pollination services in the last two decades, with a substantial growth over the last five years, which represented 54% of all publications. However, we emphasize that there is a marked lack of data on regionally important commercial crops that are essential for the food security of many millions of people, particularly in developing countries. Estimated global values of the crop pollination service, adjusted for inflation in March/2020, range widely from US$195 billion to ~US$387 (US$267-657) billion annually — due to methodology, input data and a historical increase in production costs of pollinator-dependent crops. There is an increasing trend over time in the values of crop pollination service estimates for the full set of main globally-grown crops, although estimates for specific crops are widely variable at local to regional scales. Research funding on pollination/pollinators is mainly in developed countries, which have published all the reviewed policy papers on the economic value of crop pollination services. Although the valuation of pollination services, and associated economics and policy remain embryonic areas of research, animal-mediated pollination is clearly a high-value environmental service, which greatly strengthens conservation arguments worldwide.

Keywords Animal-mediated pollination · Agriculture · Food security · Monetary values · Pollinator-dependent crops · Scientometrics

1 INTRODUCTION

Pollination is an ecosystem service of incontrovertible economic value linked to human well-being through agricultural production and food security (IPBES 2016). Pollinators impact food supply at a global scale, as pollinator-dependent crops contribute to ~35% of overall crop production by volume (IPBES 2016). It is estimated that 87 out of the 115 major crops grown worldwide depend on biotic pollination, to at least some degree, to set fruits and seeds (Klein et al. 2007). Additionally, over three quarters of the leading types of global-scale food crops rely to some extent on animal pollination for yield, quality, or both (IPBES 2016), and nearly 90% of all wild flowering plant species depend, at least partially, on animal pollination services (Ollerton et al. 2011).

It is vital that modern societies understand the importance of pollination for food security and for their very existence (Oliveira et al. 2020). The IPBES assessment on pollinators, pollination and food production recognized evidence of wild pollinator decline in northwest Europe and North America, and also identified data shortfalls and an urgent need for monitoring pollinators and pollination elsewhere in the world (IBPES 2016). The causes of pollinator decline include the indiscriminate use of pesticides, biological invasions, genetically modified (GM) crops, intensification and expansion of agricultural practices and parasites (Dicks 2016; IPBES 2016; Potts et al. 2016), as well as habitat loss and fragmentation associated with the accelerated intensification of anthropogenic actions (e.g. Potts et al. 2010; Xiao et al. 2016).

The continued expansion of human-modified landscapes is directly associated with the disruption of pollination as a diffuse ecological function (Aguilar et al. 2006; Aguilar and Galetto 2004) and service (Garibaldi et al. 2016; Gibbs et al. 2016; Ricketts et al. 2008). Populations of both pollinators and flowering plants, mainly those with specialized reproductive traits, are frequently reduced or driven to local extinction in human-modified landscapes (e.g. Girão et al. 2007; Lopes et al. 2009; Tabarelli et al. 2010). Furthermore, geographic isolation of populations in forest remnants within hyper-fragmented landscapes limits the flow of pollen among populations, further reducing plant reproductive success (e.g. Llorens et al. 2012; Ricketts et al. 2004; Ricketts et al. 2008). Agriculture is both a beneficiary of pollinator abundance and the leading driver of pollinator declines through land-use change, agro-chemical use and other traditional or mechanized large-scale farming practices (e.g. De Marco and Coelho 2004; Dicks et al. 2016).

The ongoing situation is not favourable to the maintenance of many species of pollinators, since many of these threats appear to be increasing in intensity across continents (e.g. Calderone et al. 2012; Potts et al. 2016). Meanwhile, research and development (R&D) expenditures are highly uneven across high-income (developed) and low- and middle-income (developing) countries. Available evidence suggests that returns on R&D investments should be extremely high (Goñi & Maloney 2017). In the context of agricultural R&D, in recent years, governments of middle-income nations are investing more than those of high-income, yet low-income countries invest a far lower share of GDP compared to wealthy countries, not only in R&D but also in technology licensing, managerial technologies and training (Goñi & Maloney 2017). However, worldwide investment in R&D directly related to pollination and pollinators are still poorly understood.

Continuous state-of-the-art analyses to detect predominant patterns on the status of pollination ecosystem services are necessary to identify major information gaps and to support a more effective use of natural resources associated with food production in agricultural fields. One approach is to deploy continuous assessments of the economic value of pollination in time, space and across different crops (Basu et al. 2011; Gallai et al. 2009; Hanley et al. 2015; Lautenbach et al. 2012; Leonhard et al. 2013; Winfree et al. 2011), which was reviewed by Breeze et al. (2016), Garibaldi et al. (2014) and Potts et al. (2016). The welfare impacts of an ecosystem service can be expressed in monetary terms and included as part of a cost-benefit analysis to inform policy makers. This represents an ecosystem input to agricultural production, reveals the net benefits of conserving crop pollinators and highlights the risks of declining service (Abson and Termansen 2011; Allsopp et al. 2008; Hanley et al. 2015; Hein 2009). This also provides an insight into poorly functioning institutional arrangements that fail to reflect the true socioeconomic costs of environmental degradation more generally (Radford and James 2013). Those outcomes can also bring awareness of increase productivity and land-use revenues through ecological intensification of agroecosystems (Hipólito et al. 2018; Kovács-Hostyánszki et al. 2017). Although the economic value of pollination services has been previously estimated, the amount and dynamics of research funding/grants allocations associated with the generation of policy documents related to pollination services worldwide are still poorly understood.

In this review study, we examined how the economic valuation of crop pollination services has been investigated and reported in the scientific literature, with a focus on the economic valuations themselves, as well as the investments and policy actions and government and media documents related to pollination and pollinators. We identified general trends in the scientific literature in relation to crop pollination services, the types of economic benefit and the measurement techniques applied and provide a synthesis of the previously estimated economic values of agricultural pollination at a global scale.

2 MATERIALS AND METHODS

2.1 Economy aspects of pollination services - Scientometrics and review

A systematic search and scientometric review of pollination services was carried out using quantitative techniques to map the science, policy and management contexts to quantify several aspects of the development of this area of pollination ecology (see Milojević and Leydesdorff 2013 for details on information metrics). The survey of scientific publications included all publications on crop pollination services from 1945 (the year of first publication registration in the Web of Science platform) to December 2018 (https://www.webofknowledge.com). We searched for the argument "*pollinat* service** and *econom* val**" appearing in the title, keywords and body of the text. After a careful check, we considered only articles that discuss or contain at least one form of pollination ecosystem service valuation (see Fig. 1 for details). To avoid double-counting in some of the analyses, we classified all the articles into two main groups as either qualitative studies or quantitative synthesis (meta-analysis or bibliographic survey). The screening path, exclusion criteria and final data set are detailed in the Figure 1, which is based on The PRISMA Statement: Preferred Reporting Items for Systematic Reviews and Meta-Analyses (*sensu* Moher et al. 2009; http://www.prisma-statement.org/PRISMAStatement/FlowDiagram). After the body of literature was consolidated (Appendix 1 in Electronic Supplementary Material), we classified information from all articles into 10 items for analysis (Table 1).

2.2 Estimated values of crop pollination services

To evaluate changes in the economic value of crop pollination services, by geographic locations and periods of estimation, we used the entire bibliography generated by our data mining effort. We adjusted for inflation (until March 2020) the published estimates of economic values for biotic pollination. We used as initial reference for the adjustment for inflation the publication year or the year of the database applied in the estimates if they were more than two years before the publication (see details in Table 2) (https://www.inflationtool.com). After, other currencies were converted into US dollars (US$) on the same day using common exchange rates (as April 4, 2020) available on the Brazilian Central Bank website (https://www.bcb.gov.br/conversao).

2.3 Pollinator dependence of agricultural production

We further extracted global scale data on the total amount (metric tonnes, t) of agricultural production of 2016 from the Food and Agriculture Organization database (FAOSTAT 2018) from each country that appeared in our scientometric review. We then classified the degree to which each crop type depends on biotic pollination (*sensu* Klein et al. 2007). Based on the improvement in production and quality associated with pollination by animals, the analysed crops were classified into one of the six following categories (*sensu* Klein et al. 2007): (1) essential; production is reduced by 90% or more when pollination services are lacking; (2) high: a reduction of 40% to 90%; (3) modest: a reduction of 10% to 40%; (4) little: a reduction of 0% to 10%; (5) no increase under conditions of animal-mediated pollination; and (6) unknown, when empirical studies for that crop were entirely missing. We then aggregated the classes of dependence (1 to 4) to assess the amount of pollinator-dependent agricultural production by country, compared to non-dependent (5) and unknown (6).

2.4 Research funding, government documents and policies related to pollination services

In order to review research funding/grants and government documents related to the conservation of pollinators and pollination ecosystem services worldwide, we used Dimensions Platform (https://www.dimensions.ai/). The Dimensions Platform is a new scholarly search database that focuses on the broader set of use cases. The database includes research articles and their citations, books, grants awarded, patents, clinical trials and policy documents with a standard set of research classifications employing machine-learning techniques (Hook et al. 2018). Dimensions has gathered, cleaned and rendered unambiguous a global database, while checking all sources on grant data for new data each month.

Data on research funding/grants and government documents were searched by combining the keywords: pollinator(s), pollination, sustainability, conservation, biodiversity-friendly practice, crop, agriculture and farming. The search was conducted in November 2018 and included all research funded and government documents since 1992, the year of the first record. All research funding records and government documents were individually checked for duplicates and we only considered funds that address pollinators or pollination ecosystem services as the main subject of the project proposed (see Fig. 1 for details). For government documents we considered only documents that address conservation of pollinators or pollination ecosystem services (see Fig. 1 for details). Data of scientific publications, research funding and policy documents were grouped into two categories represented by developing and developed economy countries according to the United Nations (2019).

In addition, a global media search on specialized websites was conducted for government policies with the following key words: pollination, pollinator(s), conservation, law, measure, protective, regulation, state, government, policy (see Fig. 1). Those key words were translated and applied in English, Spanish, Portuguese, German, Danish, Japanese, Italian and French to cover the largest number of countries and to minimize the Anglophone bias in conducting a search in English only.

3 RESULTS

3.1 Scientometrics of studies on the economic value of pollination services

Our search in the Web of Science returned 177 articles, 100 of which were selected to investigate the economic value of pollination services (see Table S1 in the Electronic Supplementary Material for the full list). The remaining 77 scientific articles addressed other types of ecosystem services or cited pollination as a peripheral example of ecosystem services and did not discuss or contain at least one form of pollination ecosystem service valuation.

Among the 100 articles that estimated the economic value of pollination services, 32% developed an estimate of economic values of ecosystem services (including pollination services) while 29% estimated the value of the pollination services exclusively (Fig. 2a). Other articles were case studies that explore the value of pollination for a single crop (26%) or for multiple crops (13%) (Fig. 2a). Articles investigating the economic value of pollination of coffee (N= 9) and apple (N= 4) account for 39.4% of all studies that explored at least one crop (Fig. 2b).

We observed three publications peaks in 2013, 2014 and 2016. Prior to 2006, only eight articles had been published (Fig. 3). Most of the studies (57.1%) were conducted in developed countries (i.e. the study areas were situated within developed countries), 33.3% in developing countries, while other papers had a global focus or involved no specified study area (9.5%) (Fig. 4a). Considering the affiliation of the corresponding authors, 81% were affiliated to institutions in developed countries while only 19% were affiliated to institutions in developing countries (Fig. 4b). Regarding the methodology (nature of method), 34% of all studies were represented by bibliographic surveys, while 31% were based on experimental approaches (Fig. 5a). In terms of the nature of the study, most were empirical (56%) or reviews (20%) (Fig. 5b).

Journals containing most publications were *Ecological Economics* and *Agriculture, Ecosystems and Environment*, with 10 and seven articles, respectively (Fig. 6). These journals were ranked in 2018 as number 151 and 132 among all scientific journals in environmental sciences (SCImago 2018). An article authored by Klein et al. (2007) and published in the *Proceedings of the Royal Society B* was the most cited (1403 citations until 2017); the second most cited article (authored by Gallai et al. 2009) was published by *Ecological Economics* (636 citations). These two articles set the methodological foundation applied thereafter. The Klein et al. (2007) paper established the major categories of crop pollinator dependence, whereas Gallai et al. (2009) applied these dependency categories to a widely used bioeconomic equation to estimate the economic value of pollination, which was later officially adopted by the Food and Agriculture Organization (FAO).

3.2 Spatiotemporal variation in crop pollination values

The annual economic value of pollination service globally, per unit area and for some crops, are presented on the basis of six different methods presented in Table 2. We updated the global scale pollination services estimates adjusting for inflation and converting to US$ when authors published in different currencies, current/adjusted values are US$206 billion (Costanza et al. 1997), US$324 billion (Pimentel et al. 1997), US$210 billion (Gallai et al. 2009), approximately US$387 billion (US$267-657) (Lautenbach et al. 2012), and more recently at US$195 billion (Bauer and Wing 2016). These estimates represent the fraction of global food production attributed to animal pollination and can therefore be considered as an assessment of the gross overall monetary value of animal pollination services. This of course excludes many plant food items sourced from natural ecosystems that also depend on pollination service from either native or exotic pollinators.

The fraction of national cropland production that depends on biotic pollination is variable across countries, from 27.5% in the United Kingdom to as much as 38.6% and 49.1% in Sweden and Fiji, respectively (Table 3; N= 29 countries with developed and developing economies). Combining country-scale FAO agricultural production data with our review shows that in some countries were the demand for agricultural biotic pollination services is high, there is no studies (with the study area in the country; Fig. 4a) on the economic valuation of pollination services (e.g. Argentina, France) (Fig. 7). This is particularly evident for China, which has the highest agricultural production dependent on biotic pollination and no study on the theme was developed there (Fig. 7). In addition, the total agricultural production sourced from crops for which the degree of dependence on natural pollinators is unknown is substantial and around 20-30% (from 23.2% in Sweden to 33.2% in Indonesia) in a diverse set of countries, independently if they have developed or developing economies, excepting for Fiji, where this percentage is only 1.5% (Table 3).

3.3 Research funding records related to pollination services

Our search returned 547 records of research funding related to pollination services, 217 of which were analysed in this study (see Table S2, Electronic Supplementary Material). The funded projects related to pollination services in developed countries accounted for 94.93% (N= 206) while developing countries received only 5.06% (N= 11) of the total funds (Fig. 8). Records of funds on pollination services started in 1993, increased sharply after 2006, doubling in value from 2005 to 2006, and trebling in value from 2008 to 2009 (Fig. 3). Investments exceeded US$12 million in 2010, reaching a maximum of US$14 million in 2016 (Fig. 3). There was a positive temporal correlation between the scale of investments and number of publications (r= 0.80, $P < 0.0001$).

The overall research funding contributions on pollination service researches from 1992 to 2018 exceeded US$ 155 million; 23 countries received funds, which ranged from US$0.016 million in India to US$51.3 million in the United States (Fig. 8). The highest investments were in the United States (US$51.3 million) and the UK (US$25.5 million). Together these two countries received 79.6% of the investments. The United States and the United Kingdom were also the countries with more scientific publications in the literature body in our review (Fig. 4a; Fig. 8). Among the developing countries, Colombia (US$1.23 million) and Brazil (US$1.14 million) received the highest amount of research funding, however together they accounted for only 1.53% of investments (Fig. 8).

3.4 Government documents and policies related to pollination services

The search returned 306 government documents. After removing duplicates and documents that did not match our screening criteria (see Fig. 1 for details), 24 documents remained in the analysis (see Table S3 in the Electronic Supplementary Material). The 24 government documents were published by Canada (N=1), France (N=1), European Union (N=1), Australia (N=2), the government and parliament of the United Kingdom (N= 11) and FAO (N= 8). These government documents addressed the following five major themes: (1) status, monitoring and preservation of pollinators; (2) pollinator conservation strategies; (3) reports and recommendations on the use of pesticides, especially neonicotinoids; (4) Actions and recommendations for healthy environments for pollinators; (5) value of pollinators in agriculture, ecological intensification and sustainable agriculture.

Our internet media search returned nine positive ongoing policies to protect pollinators and pollination ecosystem services. These documents were initiatives (N=5), laws (N=3), and decree (N=1) in effect between 2011 and 2018 in France, Canada, Ireland, Australia, Porto Rico and European Union. The measures deliberated over the five main topics covered in government documents (mentioned above), but also addressed the improvement of knowledge on pollination and pollinators and established efforts to increase socio-awareness about the preservation of pollinators and their importance for human well-being. These policies are summarized in Table S4 of the Electronic Supplementary Material.

4 DISCUSSION

4.1 Economic value of pollination services: scientometric perspective

Our results indicate an increase in the number of economic valuation studies focused on pollination services in the last two decades, with a substantial growth in the last six years to 2018 (ca. 55% of all publications). However, there is a marked lack of data on regional and local important commercial crops that are essential for the food security of many millions of people, particularly in tropical developing countries (e. g. acerola in south America (Schreckinger et al. 2010); baobab in eastern Africa (Meinhold et al. 2016)). Those data could support future discussions on the economic contribution of pollinators to agricultural production at different scales. The available studies on the economic benefits of pollination services have not yet been well incorporated into public policy formulation and decision making (Breeze et al. 2016).

In our analyses there were only four articles based on experimental research in tropical environments (Bos et al. 2007; Bravo-Monroy et al. 2015; Cunningham and Le Feuvre 2013; Sandhu et al. 2016), all of which assessed the contribution of pollinators to commercial crops grown across the tropics (e.g. coffee, passion fruit and cocoa). The value of pollination services to many crops grown at smaller continental scales remains entirely unknown.

Despite recent attention on applied pollination ecology, there is still a major research gap linking crop pollination requirements to the conservation of pollinators and natural habitats around the world (Breeze et al. 2016). Most agricultural pollination ecologists are based and work in temperate countries. We believe that more experimental analyses under different environmental and socioeconomic contexts should be conducted in tropical agroecosystems, especially in emergent developing countries, such as China and Brazil, where agricultural production from food crops that are highly dependent on pollinators is expanding rapidly (Giannini et al. 2012; Giannini et al. 2015a). The relationship between pollination services and agricultural production is often diverse and context-specific, which makes it difficult to apply the lessons learned from studies in Europe and North America to the rest of the world. However, those gaps provide research opportunities to understand what would be more suitable, in terms of research strategies, for developing countries (Timberlake and Morgan 2018).

Increased technology favours access to information that may have resulted in a growing number of published articles over time. Although some studies were carried out in developing countries (29.4%), one third of them were led by authors affiliated with developed (and mid-latitude) countries. Economic factors contribute to the higher science productivity of wealthier nations, while some countries with greater agricultural potential continue subject to scarcity of research (Moreddu et al. 2017). After the USA, the following countries appear sequentially in terms of number of publications per country of the corresponding author: the UK, Germany, Brazil, Canada and Australia (Fig. 4b). However, Australia ranks 31st in the world ranking of agricultural production, whereas Brazil is now the world's fourth largest food producer, the third largest food exporter, the third fruit producer (MAPA 2017) and the leading nation in terms of productivity growth (Bojanic 2017; Hubbard et al. 2017; Moreddu et al. 2017), but even so, the dependence on pollinators of 1/3 of its agricultural production is still unknown (Table 3, source FAOSTAT 2018).

4.2 Economic value of pollination services

Our review and synthesis found recent literature showing a growing trend in the global scale monetary value of pollination services, due to methodological improvements and increasing production and market prices of pollinator-dependent crops (Breeze et al. 2016; Hanley et al. 2015; Lautenbach et al. 2012). Despite this increasing trend over time in the estimated values of pollination services from the full set of main globally grown crops, when individual crops are analysed at local and regional scales the economic contribution of pollination to some crops varies greatly and does not follow this global pattern (see Table 2).

In 2004, the economic value of coffee pollination in Brazil was estimated at US$2,595.42/ha (Marco and Coelho, 2004), in 2006 it was estimated in Indonesia and Ecuador at US$63.55/ha and US$112.33/ha respectively (Olschewski et al. 2006), while in 2015 the estimated value was US$159/ha in Colombia (Bravo-Monroy et al. 2015) (all values adjusted for inflation until March 2020, Table 2). These fluctuations in local estimates varies mostly due to methodological differences, such as the accuracy of the database, the diversity of experimental design in field researches and even the equation applied to estimate the value. Although methodologies have become increasingly sophisticated, the studies available to date have generally failed to propose new approaches that can easily be applied to diverse localities and cultural contexts, rendering difficult comparisons of different scenarios that can be used to extrapolate results (see Bauer and Wing 2016; Gallai et al. 2009).

Most studies on the economic value of pollination services at regional scales emphasize that enhanced levels of pollination and pollinator abundance increase the economic value of production by improving qualitative aspects of fruit and/or seed yields, their nutritional content, and general appearance including fruit size (e.g. Matheson and Schrader 1987; JianDong and Chen 2011; Lye et al. 2011; Garratt et al. 2014; Breeze et al., 2015; Giannini et al. 2015a; Giannini et al. 2015b; Knapp and Osborne 2017). For example, in general, a production increase of between 5% and 50% can be achieved with an adequate animal pollination service, mainly represented by bees (e.g. Greenleaf and Kremen 2006; Gallai and Vaissière 2009; Stanley et al. 2013). Specifically for strawberry, the commercial value of strawberry pollinated by bees increases by 38.6% compared with wind-pollinated production, and by 54.3% compared with self-pollination (Klatt et al. 2014). The persistence or restoration of natural habitats embedded within agricultural landscapes for pollination services can be as cost-effective and productive as conventional agricultural approaches, justifying the retention of as much as 8% of spared habitat supporting wild pollinators in relation to overall cropland area (Dicks et al. 2016).

Our comprehensive survey found five estimates on the global value of agricultural pollination, reported by Bauer and Wing (2016), Costanza et al. (1997), Gallai et al. (2009), Lautenbach et al. (2012), and Pimentel et al. (1997). Although the values reported were increasingly higher over time, the comparison among these values is difficult due to differences in data input and methodologies applied. The seminal paper by Costanza et al. (1997) estimated the value of pollination services from the overall production value of pollinator-dependent crops, honey and beeswax in the USA. These values were then simplistically extrapolated to analogous agricultural production in the rest of the world by assuming that agricultural products in the USA are equivalent to 10% of the global value. Pimentel et al. (1997) estimated the economic value of insect pollination worldwide to be at least five times higher than the value estimated by Robinson et al. (1989) for the USA. The annual estimates from either Costanza et al. (1997) or Pimentel et al. (1997), adjusted for inflation and exchange rates until March 2020, are around US$206 billion and US$324 billion, respectively. The estimate of Pimentel et al. (1997) was relatively high because they included the value of insect-pollinated legumes that are fed to cattle. When it is considered in their estimated value of pollination service only the crops used directly for humans, the estimated value will represent ~US$64 billion (adjusted for inflation in March 2020). These values (US$206 billion and ~US$64 billion) are lower than the US$210 billion estimated by Gallai et al. (2009), which, according to them, is ~9.5% of the total value of the crops used directly for human food. Costanza et al. (2014), more recently, provided a new estimate based on updated data on global agricultural production and land use change between 1997 and 2011. Unfortunately, however, they only presented aggregate global values, categorised by biomes, without differentiating ecosystem services individually, and in doing so completely omitted the contemporary value of pollination services at a global scale.

Even while accounting for several valuation components that had been entirely neglected in previous estimates, Gallai et al. (2009) did not consider supply-demand curves in market responses to insufficient yields, since a generalized decline in pollinators can lead to increased prices of pollination-dependent crops (Hein 2009). Gallai et al. (2009) recognized this bias and assumed the importance of price elasticity and market responses, but they did not apply this concept to more accurately adjust their estimate. The global value estimated by Lautenbach et al. (2012), ~US$387 billion (adjusted for inflation in March 2020, see Table 2), is the highest of those published so far and was 1.9 times higher than the value estimated by Gallai et al. (2009). The use of purchasing power parities (PPPs) to compare realistic values between different countries substantially raises the final value of pollination services since it increases the value in almost all developing countries, where labour input tends to be cheaper. This effect is stronger than any reduction in pollination values in developed countries (Lautenbach et al. 2012), making a global estimate even higher than otherwise expected.

The most recent estimate of the overall monetary value of crop pollination is US$195 billion (adjusted for inflation in March 2020) (Bauer and Wing 2016). This estimate considered the benefits of pollination across all sectors, including indirect effects on meat, vegetable oils and fats, dairy products, and beverages, nevertheless this value is lower than adjusted values of the previous estimates. Interestingly the estimate by Gallai et al. (2009), which computed benefits only from crops directly consumed by humans and that are dependent on biotic pollination (US$210 billion), is still slightly higher than the value estimated by Bauer and Wing (2016), both adjusted for inflation in March 2020.

4.3 Comparison among methods for economic valuation of pollination services

Based on the analysed articles, six distinct methods of economic valuation of pollination services are often applied (see Table 2). Differences in these approaches are mainly based on crop market prices, losses in yield production associated with pollination disruption, and the association between production and prices. The most frequent method to estimate the economic value of pollination services has employed yield analysis (YA), which simulates the absence and presence of animal pollination in field experiments following proposals of Klein et al. (2007). The dependency ratio (DR), represented by the maximum benefits of pollination services for cultivated species, is frequently applied together with production data in order to estimate the economic value of pollination, according to the analysed articles (Basu et al. 2011; Calderone 2012; Giannini et al. 2015b; Lautenbach et al. 2012). Although the dependence of pollinators was at some level previously considered by authors, this improved standard procedure has been widely applied in many case studies (Basu et al. 2011; Calderone 2012; Giannini et al. 2015b; Lautenbach et al., 2012). Crop value (CV) is a sum of crop market prices positively affected by pollination services (e.g. Constanza et al. 1997). Replacement costs of pollinators (RC) with technological solutions or management of pollinators is considered an accurate alternative for estimating the ecosystem value of pollinators (Allsopp et al. 2008). Similarly, the consumer surplus (CS) method applies partial and general equilibrium models to analyse market responses to changes in production due to pollination deficit, the ability of producers to compensate for losses with other inputs, and the effects these losses would have on the external market (Bauer and Wing 2016; Gallai et al. 2009). Articles also valuated pollination ecosystem services on the basis of citizen's willingness to pay (WTP) for the maintenance or improvement of nonmarket benefits, in this case pollination benefits, through a questionnaire-based economic survey (Breeze et al 2015). For local scales, YA analyses are more frequently applied. Alternatively, at global and regional scales, DR is more frequently applied and tends to generate higher values of pollination services compared to the other methods, according to our review.

Studies on pollination services in agricultural landscapes are complex and have been conducted to improve the understanding of the ecology of pollinators, the relationship of pollinators with landscapes, and crop yields (Breeze et al., 2016; Nogué et al. 2016). The density of floral visitors, the level of agricultural conventional intensification and the isolation of semi-natural or natural areas are the factors that most influence pollinator-dependent crop yields

(Grêt-Regamey et al. 2014). Ricketts et al. (2004) demonstrated that two isolated tropical rainforest fragments (46 and 111 hectares with a distance of 1 km from extensive natural habitat) increased coffee yields by 20% and reduced the frequency of deformed seeds by 27% through pollination services, generating a surplus of US$60,000 per year for a Costa Rican farm. This amount was equivalent to 7% of annual profits and represented a much larger amount than current conservation incentive payments (Ricketts et al., 2004). The increase in natural habitats in agricultural landscapes can be as cost-effective and productive as conventional approaches, even with up to 8% of land use for habitats that support beneficial organisms (Dicks et al. 2016).

High quality pollination services, associated with high density and diversity of pollinators, also increases the economic value of crop production by improving qualitative aspects of fruits such as their appearance, size and nutritional quality (Garratt et al. 2014; Giannini et al. 2015). Gallai and Vaissière (2009) observed a production increase of between 5% and 50% induced by adequate biotic pollination service, mainly by bees. The commercial value of strawberry pollinated by bees increased by 38.6% compared to wind-pollinated production and by 54.3% compared to self-pollination (Klatt et al. 2014). Bees homogeneously allocate pollen into the receptacles, increasing the number of fertilized achenes in each fruit, which are responsible for the production and accumulation of auxin and gibberellic acid (Klatt et al., 2014). Together, these hormones induce cell growth and size, thus increasing the weight of individual strawberry fruits (Klatt et al. 2014).

Although methodological adjustments have been developed to address yield responses to pollination services (Breeze et al. 2016, Winfree et al. 2011), a major fraction of pollination-dependent fruit and vegetable crops consumed by humans is derived from diffuse systems of subsistence production or those commercialized only in informal local markets, so that both country-scale productivity and production values fail to be monitored and accounted for in estimates. Additionally, most crops important for human diets are not export commodities but constitute essential sources of vitamins and minerals, most of which are produced at local to regional scales (Eilers et al. 2011). Also, many plants cultivated at local scales or extracted from natural ecosystems are not even considered as crops, such as *Platonia insignis*, *Endopleura uchi*, *Myrciaria dubia*, *Astrocaryum aculeatum*, *Pouteria caimito*, *Caryocar villosum*, *Spondias mombim*, *Byrsonima crassifolia* in Brazil, even though they remain essential for local food security for millions of people, particularly in the context of family household and subsistence farming (EMBRAPA 2016). Many of these minor ´crops´ have no export markets, are missing altogether from the periodically updated FAO agricultural databases and are, therefore, entirely unaccounted for. Nevertheless, this data shortage for crop plants such as those mentioned above (and many others elsewhere in Asia and Africa) may indicate that economic benefits of pollination to food production worldwide have been underestimated. The magnitude of this discrepancy remains unclear given the data available and mainstream economic rationale at present. Additionally, estimates fail to consider other economic values of pollination services such as in providing raw materials for cosmetics and pharmaceutical industries, plants for florist trade, beehives and honey, for example.

Assessments of ecosystem services that consider only monetary aspects are limited, as several ecosystem benefits, such as pollination, are not accounted for in economic markets and are ecologically and socially context-dependent. In addition to economic evaluation, a multidimensional analysis is therefore essential to promote a balance between the financial, social, physical, human needs, and the natural environment, to ensure the maintenance of pollination services and human wellbeing (see Hipólito et al. 2016; Garibaldi et al. 2016). Surveys that demonstrate the broad range of measures that farmers and communities can or have been using that are beneficial to pollinators are important to demonstrate "win–win" scenarios and are highly appropriate to ensure better land-use decisions than several conventional agriculture practice (e.g. Garibaldi et al. 2016; Hipólito et al. 2016; Olschewski et al. 2006).

4.4 Research funding and government responses to pollination services

Developed countries received more research funding for projects related to pollination services compared to developing countries. Additionally, developed countries published all the policy documents on pollination service protection. The main pathway to grow a science base is through financial investments. Targeted public or private sector financial contributions to research projects or research training are essential for high-quality scientific research, for science capacity and more comprehensive and diversified research enterprises at larger scales. For example, the United States, Germany and Canada on average allocate 2.15% of their Gross Domestic Product to scientific research, twice the amount invested in Brazil (World Bank in 2012). Research funding contributions for pollination research in the 1992-2018 period exceeded US$115 million, and the highest investments were in the United States (US$85 million) and the UK (US$36 million).

Undeniably, global development required further efforts from wealthy developed countries to reconcile priorities, particularly for low-income developing countries. Although, some grants were designated to research in developing countries (in Brazil, Ethiopia, Mexico), 7 out of 11 were assigned to organizations located in developed countries (i.e. the United Kingdom, United States, Italy). In the last decade approximately 6% of all the UK research funding is estimated to involve developing countries or have direct relevance to international development (Timberlake and Morgan 2018). This may deliver research funding and expertise to countries that have been historically neglected, contributing to build valuable research capacity.

Many countries are building a consistent national policy framework to translate the wide body of research and management recommendations for pollination services into government policies (Table S4, Electronic Supplementary Material). Initiatives such as the IPBES pollination assessment (IPBES 2016) and the publication of 10 simple policy recommendations to safeguard pollination and pollinators (Dicks et al. 2016) could be applied to reinforce and support more effective policy decisions (e.g. “recognize pollination as an agricultural input in extension services”; “develop long-term monitoring of pollinators and pollination”; “fund participatory research on improving yields in organic, diversified, and ecologically intensified farming”). Recently, documents describing an effective framework have been published (Table S3). These government documents may be used by local researchers and technical consultants to strengthen more locally relevant recommendations, as well as update data and foster insights. However, stronger political will is required to implement such initiatives and put into practice well-established endorsements. This could evolve in a variety of ways, for example, through greater public awareness and pressure. Public interest in natural pollinators has recently grown in South Africa through social media, photography and citizen science, demonstrating increased civic and political engagement with these issues (Timberlake and Morgan 2018).

Furthermore, government responses are widely variable in content and in space and time. For example, in 2018, the EU banned neonicotinoids, the world’s most widely used insecticides, and many European countries are planting wildflowers and subsidizing agricultural set-asides to attract insects (Timberlake and Morgan 2018). Controversially, in the same period the Brazilian government regressed when pro-agribusiness congressmen voted to lift restrictions on harmful pesticides that are strictly banned in other countries.

5 CONCLUSIONS AND RECOMMENDATIONS

We documented that since the 1990s there has been a rapidly increasing trend of published estimates on the economic value of biotic pollination services, often highlighting the rising costs of the service in degraded landscapes. Although we observed an increasing pattern of estimates of global pollination values, same crops local and regional estimates tend to fluctuate over time and geographically. Rather than propose a simplification of methodologies, we encourage pluralism based on a wide range of approaches at multiple scales under different ecological and socioeconomic contexts that span from mechanized croplands serving global export markets to small-scale horticulture in local subsistence economies. To achieve this goal, will require an expansion of research since the current dearth of experimental data, especially for locally-grown crops in tropical countries, will continue to perpetuate the severe underestimation of biotic pollination services from published values. Besides, estimates overlook other important economic values of pollination services such as in honey and beehives chain and in cosmetics and pharmaceutical industry.

However accurate we may be in estimating the value of pollination services, this value continues to fail in representing the complex sets of benefits of pollinators and describe the full importance of their ecological functions. It is widely known that pollination services provided by natural ecosystems influence the diversity and intensity of interactions between pollinators and crops, and many other plant species used for food by subsistence communities or in commerce, which are not usually defined as crops. All these caveats contribute to the continued systematic undervaluation of biotic pollinators in agroecosystems. Nonetheless the current incomplete literature on crop pollination services already reveals that the benefits of pollination for agriculture are very high, even if underestimated, which should strengthen the conservation and land-use planning agenda in human-modified landscapes around the world.

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CONFLICT OF INTEREST

The authors declared that they have no conflict of interest.

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LEGENDS TO THE FIGURES

Fig. 1 Flow diagram representing the body of literature reviewed, research funding and government documents and policies considered in this study of pollination ecosystem services (including counts of sources and exclusion criteria used to filter the body of literature, grants and policy documents into the final dataset reviewed. Search argument for the scientometric analysis in the Web of Science: "*pollinat* service** and *econ* val**"; search arguments for research funding in Dimensions Platform (2018; (https://www.dimensions.ai/): pollinator(s), pollination, sustainability, conservation, biodiversity-friendly practice, crop, agriculture and farming; search arguments for Government documents and policies in Dimensions Platform (2018) and specialized media: pollination, pollinator(s), conservation, law, measure, protective, regulation, state, government, policy (keywords were searched in English, Spanish, Portuguese, German, Danish, Japanese, Italian and French). This diagram is based on The PRISMA Statement: Preferred Reporting Items for Systematic Reviews and Meta-Analyses (*sensu* Moher et al. 2009; http://www.prisma-statement.org/PRISMAStatement/FlowDiagram).

Fig. 2 Articles containing estimates of the economic value of pollination services. (a) Number of articles that developed an economic valuation estimate of ecosystem services (including pollination services - ES), pollination service (PS), economic values of pollination services of a single crop (SC), and estimated value of pollination for multiple crops (MC) (N= 100). Reviews and meta-analyses were included in the ES or PS bars depending on their focus. (b) Number of articles containing economic estimates of pollination services of at least one crop (N= 33). Searches were carried out using the Web of Science with the argument "*pollinat* service** and *econ* val**".

Fig. 3 Number of published papers on the economic valuation of pollination services over time. This body of literature contains 100 papers that discuss or contain at least one form of pollination service valuation (Source: Web of Science). Line represent the 217 records of investments in projects that address pollinators or pollination as an ecosystem service as the main project subject (Source: Dimensions Platform 2018; https://www.dimensions.ai/). We observed a positive correlation between level of investments and number of publications (r= 0.80, $P < 0.0001$).

Fig. 4 Number of articles on the economic valuation of pollination services classified by (a) articles with study areas in these countries (N= 63; review articles and meta-analyses were not included) and (b) countries whose corresponding authors were affiliated to (N= 100 including review articles and meta-analyses). Searches were carried out using the Web of Science with the argument "*pollinat* service** and *econ* val**".

Fig. 5 Number of articles on the economic valuation of pollination services classified by the nature of (a) the method and (b) the study. Our body of literature contains 100 articles that discuss or contain at least one form of pollination service valuation.

Fig. 6 Number of articles on the subject of pollination service valuation per journal until 2018. Search was made in the Web of Science with the argument "*pollinat* service** and *econ* val**". Our search returned a total of 177 articles, 100 of which explicitly focused on crop pollination services. Total number of journals: 62; the category "others" includes 49 journals, each of which with only one article.

Fig. 7 Distribution of agricultural production and research effort in countries that appeared in the scientometric survey in this study. Countries that produce any crop dependent on biotic pollination and appeared in our search are coloured in two categories: developed or developing economies according to the United Nations (2019) (N= 29 countries). Bubble size indicates the proportional production (tonnes) of all pollination-dependent crops in each country during the year of 2016 (according to the FAO database); values are informed in the box at right. Bubble color represents the number of published articles on economic valuation of pollination services by countries in which the studies were carried out (i.e. study area in the country) until December 2018 (Source: ISI Web of Science; https://www.webofknowledge.com). For the inclusion and exclusion criteria when searching articles at ISI Web of Science, please see the Flow diagram in Figure 1

Fig. 8 Distribution of research funding and effort in countries that appeared in the scientometric survey in this study. Countries that received any research funding/grant and appeared in our search are coloured in two categories: developed or developing economies according to the United Nations (2019) (N= 23 countries). Bubble size indicates the amount of research funding in million dollars (US$). Bubble colour represents the number of published articles on the economic valuation of pollination services in countries with developed and developing economies until December 2018 (Source: ISI Web of Science; https://www.webofknowledge.com). Source for research funding/grants: Dimensions Platform (2018; https://www.dimensions.ai/). For the inclusion and exclusion criteria when searching articles at Web of Science, please see the Flow diagram in Figure 1

Table 1 Items and categories selected for the scientometric analysis of the economic valuation of pollination services (adapted from Viana et al. 2012).

Items for analysis	Categories
1. Publication year	-
2. Correspondence author	-
3. Country of the author of correspondence	-
4. Authors	-
5. Article title	-
6. Journal	-
7. Study Area (country)	
8. Nature of study	1. editorial, 2. modelling, 3. opinion, 4. conceptual, 5. meta-analysis, 6. review, 7. empirical
9. Nature of method (Methodology)	1. descriptive, 2. modelling, 3. meta-analysis, 4. observation (sampling), 5. experimental, 6. bibliographic survey
10. Economic situation of correspondence author's country and study area according to UN	1. developed, 2. developing

Table 2 Publications containing annual estimates of the economic benefits of biotic pollination services. Economic estimation methods include: 1. CV, crop value; 2. DR, dependency ratio; 3. CS, consumer surplus, 4. RC, replacement costs, 5. YA, yield analysis, and 6. WTP, willingness to pay. Published values, current values after adjusted for inflation until March 2020 (https://www.inflationtool.com) and converted into US dollars (US$) through the Brazilian Central Bank website (https://www.bcb.gov.br/conversao).

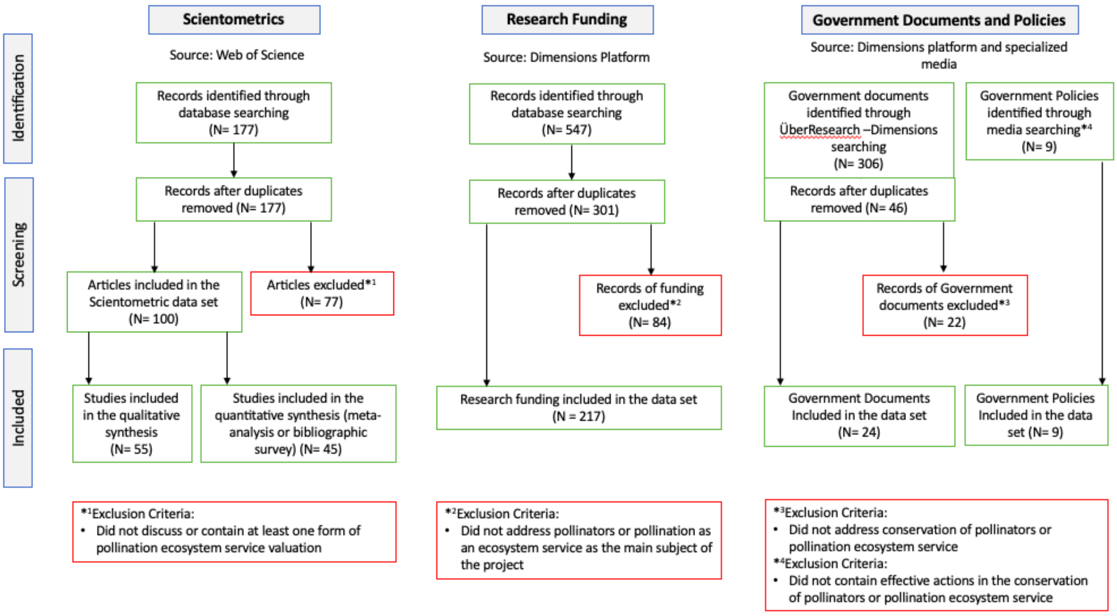
GLOBAL VALUE OF BIOTIC POLLINATION SERVICE			METHOD	Published value (for one year)	Current value (for one year)
Costanza et al. 1997			CV	US$117 billion	US$206 billion[1]
Pimentel et al. 1997			DR	US$200 billion	US$324 billion[2]
Gallai et al. 2009			DR	€153 billion	US$ 210 billion[1]
Lautenbach et al. 2012			DR	~US$340 billion (235-577 billion)	~US$387 billion[1] (267-657 billion)[1]
Bauer and Wing 2016			DR	US$140 billion	US$195 billion[1]
BIOTIC POLLINATION SERVICE FOR A SINGLE COUNTRY	**COUNTRY**	**CROP**	**METHOD**	**Published value (for one year)**	**Current value (for one year)**
Matheson and Schrader 1987	New Zealand	-	CV	£1.83 billion	US$5.4 billion[2]
Robinson et al. 1989	USA	-	DR	US$9.3 billion	US$19 billion[2]
Allsopp et al. 2008	South Africa	6	RC	US$358 million	US$484 million[1]
JianDong and Chen 2011	China	44	DR	US$52.2 billion	US$63 billion[1]
Basu et al. 2011	India	6	DR	US$726 million	US$888 million[1]
Calderone 2012	USA	58	DR	US$15.2 billion	US$18 billion[1]
Giannini et al. 2015b	Brazil	87	DR	US$12 billion	US$13 billion[1]
Breeze et al. 2015	UK		WTP	£379 million	US$512 million[2]
BIOTIC POLLINATION SERVICE FOR A SINGLE CROP	**COUNTRY**	**CROP**	**METHOD**	**Published value (for one year)**	**Current value (for one year)**
Marco and Coelho 2004	Brazil	Coffee	YA	US$1860.55/ha	US$2,595.42/ha[1]
Whittington et al. 2004	Canada	Tomato	YA	US$2700/ha	US$3,767.54/ha[2]
Greenleaf and Kremen 2006	USA	Sunflower	YA	US$26 million	US$37 million[1]
Olschewski et al. 2006	Indonesia and Ecuador	Coffee	YA	US$43-76/ha	US$63.55 – 112.33/ha[1]
Winfree et al. 2011	USA	Watermelon	RC, YA, CS	US$0.18 million, US$2.25 million, US$3.4 million	US$0.24million,[1] US$3.04 million[1], US$4.5 million[1]
Lye et al. 2011	UK	Raspberry	RC	£1170/ha	US$1,737.27/ha[2]
Garratt et al. 2014	UK	Apple	YA	£36.7 million	US$50 million[2]

Stanley et al. 2013	UK	Rape	YA	€3.9 million	US$4.5 million[2]
Bravo-Monroy et al. 2015	Colombia	Coffee	YA	US$146/ha	US$159/ha[2]
Gibbs et al. 2016	Canada USA	Blueberry	YA	US$20,655/ha US$26,541/ha	US$22,457/ha,[2] US$28,857/ha[2]
Knapp and Osborne 2017	UK	Courgette	YA	£166/ha	US$219.57/ha[2]
Klatt et al. 2014	European Union	Strawberry	YA	US$0.32 billion	US$0.35 billion[2]

[1]adjusted for inflation using year of the database applied for the estimate; [2]adjusted for inflation using year of publication.

Table 3 Total production of crops dependent on pollinators (PPDC), non-dependent on pollinators (PPNDC) and crops with unknown dependence (PUPDC). Production is represented in tonnes per country and in percentages according to their dependence on biotic pollinators (*sensu* Klein et al. 2007). Source: FAOSTAT (2018).

Developed countries	PPDC	PPNDC	PUPDC
Australia	61,527,350 (29.9%)	83,335,583 (40.5%)	60,961,506 (29.6%)
Austria	9,522,888 (31.5%)	11,383,760 (37.5%)	9,415,382 (31%)
Canada	66,252,327 (29.1%)	96,360,308 (42.3%)	65,168,062 (28.6%)
France	87,948,129 (30.5%)	115,452,783 (39.8%)	85,999,980 (29.7%)
Germany	68,780,660 (30.2%)	92,109,554 (40.2%)	67,765,768 (29.6%)
Greece	15,233,830 (33.2%)	16,545,083 (35.8%)	14,314,898 (31%)
Italy	49,304,577 (32.9%)	54,165,518 (36.4%)	46,003,355 (30.7%)
Netherlands	16,681,963 (31.9%)	18,906,795 (36.2%)	16,681,963 (31.9%)
New Zealand	3,542,208 (35.4%)	3,558,494 (35.8%)	2,884,806 (28.8%)
Poland	55,009,369 (32.6%)	62,234,804 (36.9%)	51,409,240 (30.5%)
Portugal	6,498,914 (34.2%)	6,338,636 (33.4%)	6,130,615 (32.4%)
Spain	60,179,009 (32.7%)	65,355,985 (35.5%)	58,286,481 (31.8%)
Sweden	4,159,770 (38.6%)	4,118,210 (38.2%)	2,484,110 (23.2%)
Switzerland	2,871,381 (32.9%)	3,110,822 (35.7%)	2,724,717 (31.4%)
United Kingdom	23,423,466 (27.5%)	38,219,404 (44.9%)	23,423,466 (27.6%)
United States	696,213,697 (32.5%)	752,107,302 (35.2%)	687,674,422 (32.3%)
Developing Countries	**PPDC**	**PPNDC**	**PUPDC**
Argentina	148,357,072 (32.2%)	165,794,668 (35.9%)	147,232,164 (31.9%)
Brazil	1,032,885,154 (33.3%)	1,038,725,172 (33.7%)	1,022,405,968 (33%)
China	1,658,171,076 (33.6%)	1,737,252,639 (35.2%)	1,534,303,239 (31.2%)
Colombia	65,492,621 (33.5%)	65,565,035 (33.6%)	64,480,569 (32.9%)
Costa Rica	12,531,627 (33.5%)	12,561,997 (33.6%)	12,315,569 (32.9%)
Ecuador	23,896,604 (33.4%)	23,878,403 (33.5%)	23,717,493 (33.1%)
Fiji	1,973,653 (49.1%)	1,981,662 (49.4%)	63,679 (1.5%)
Indonesia	364,677,581 (33.5%)	363,891,746 (33.3%)	362,778,268 (33.2%)
Israel	3,829,747 (35.8%)	3,778,445 (35.3%)	3,094,828 (28.9%)
Kenya	20,765,746 (33.9%)	20,823,175 (34.1%)	19,572,983 (32%)
Madagascar	13,133,041 (33.4%)	13,458,383 (34.3%)	12,721,257 (32.3%)
Mexico	134,244,810 (33.3%)	135,226,168 (33.7%)	133,051,113 (33%)
South Africa	36,686,182 (33.5%)	37,565,084 (34.3%)	34,960,524 (32.2%)



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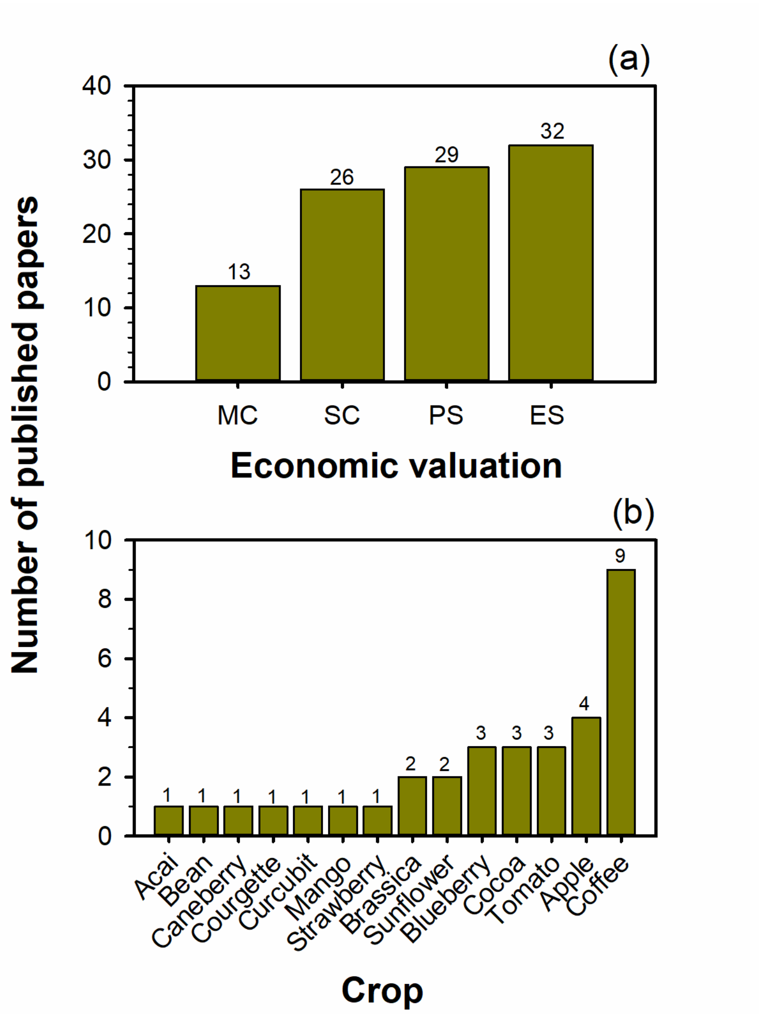

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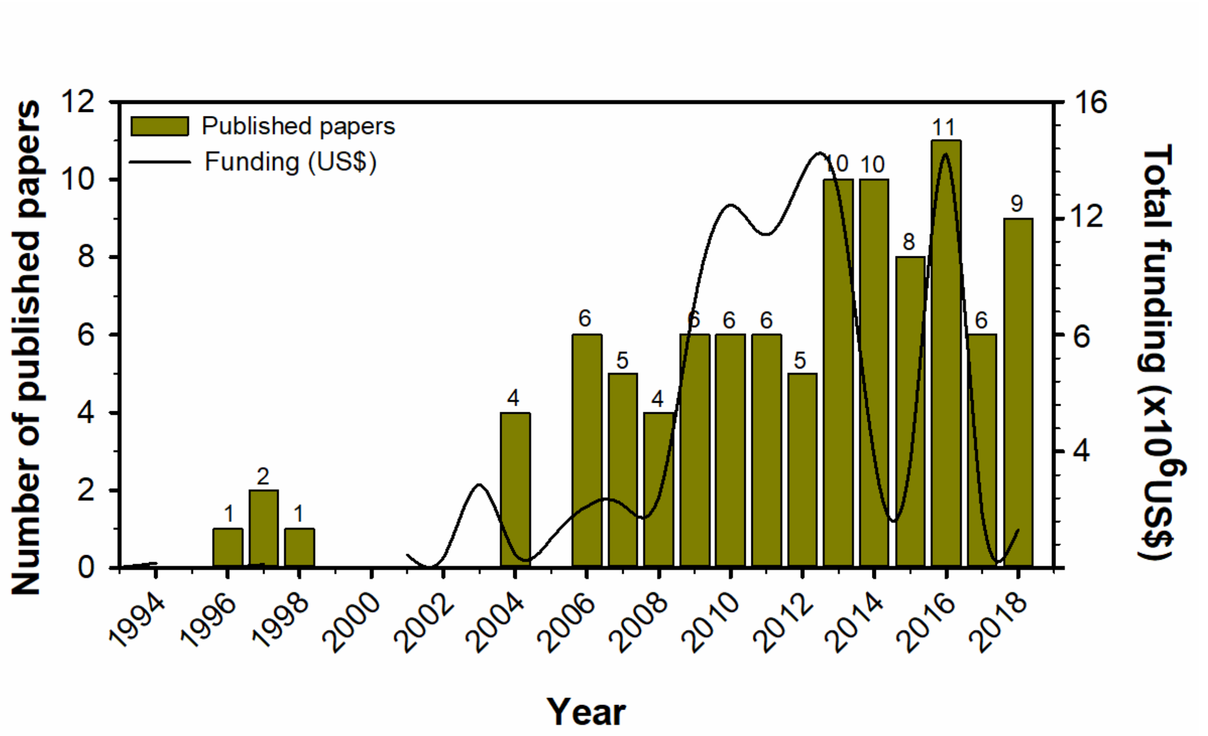


Fig. 3 Number of published papers on the economic valuation of pollination services over time. This body of literature contains 100 papers that discuss or contain at least one form of pollination service valuation (Source: Web of Science). Line represent the 217 records of investments in projects that address pollinators or pollination as an ecosystem service as the main project subject (Source: Dimensions Platform 2018; https://www.dimensions.ai/). We observed a positive correlation between level of investments and number of publications ($r = 0.80$, $P < 0.0001$).

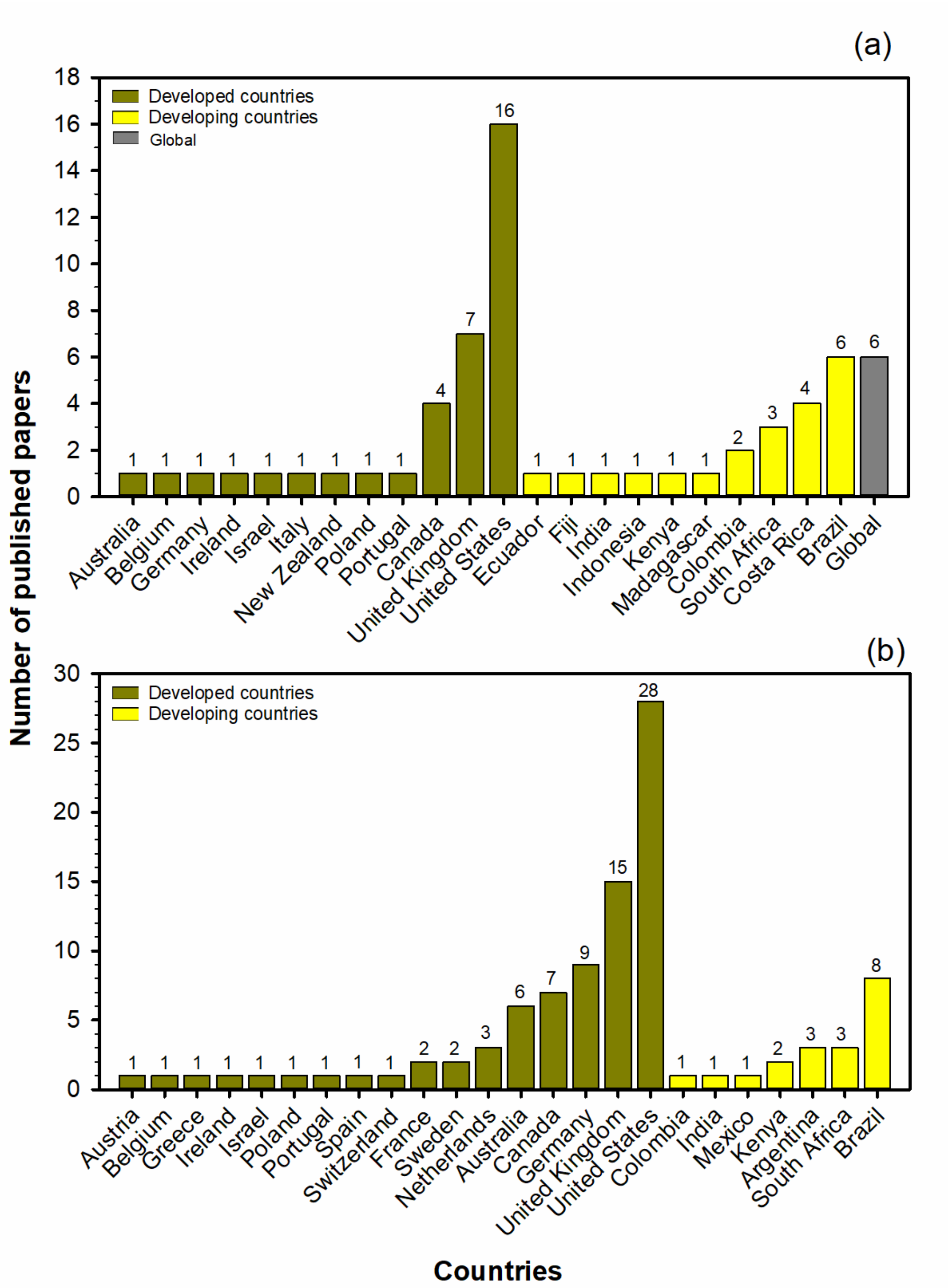


Fig. 4 Number of articles on the economic valuation of pollination services classified by (a) articles with study areas in these countries (N= 63; review articles and meta-analyses were not included) and (b) countries whose corresponding authors were affiliated to (N= 100 including

review articles and meta-analyses). Searches were carried out using the Web of Science with the argument "*pollinat* service** and *econ* val**".

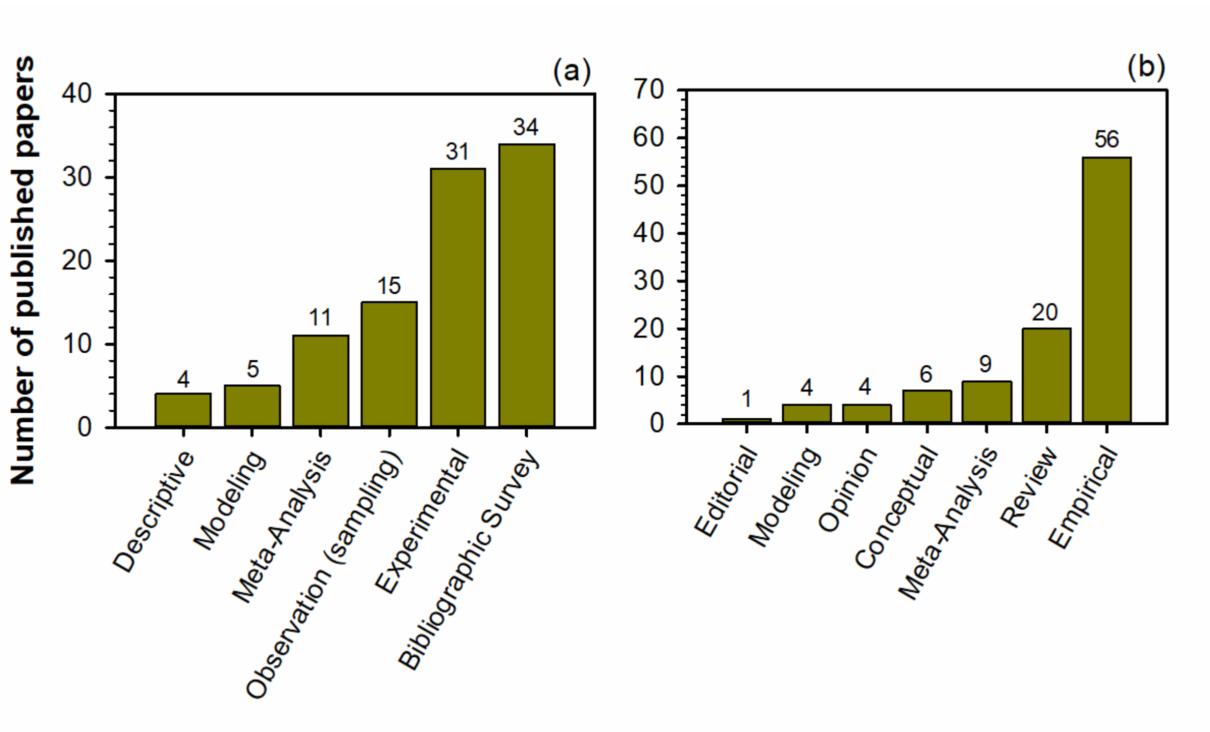


Fig. 5 Number of articles on the economic valuation of pollination services classified by the nature of (a) the method and (b) the study. Our body of literature contains 100 articles that discuss or contain at least one form of pollination service valuation.

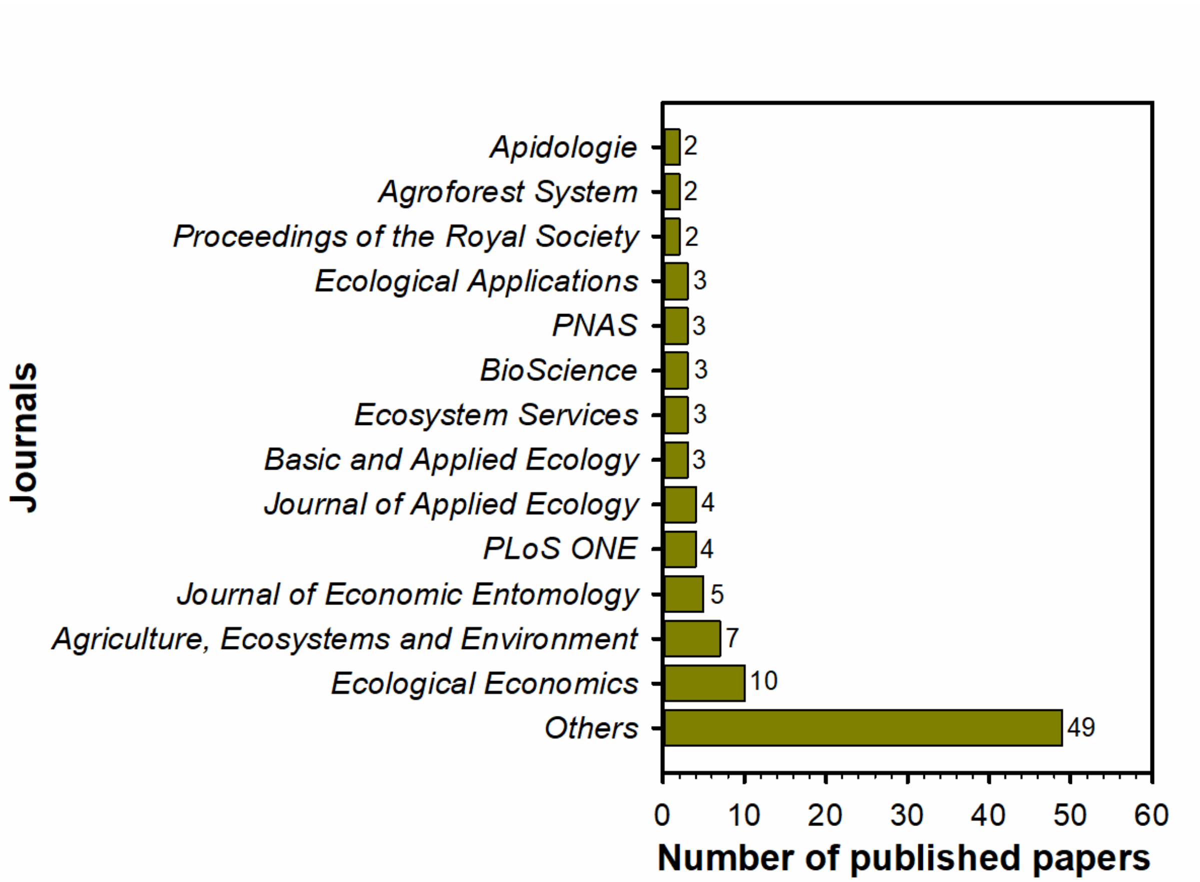
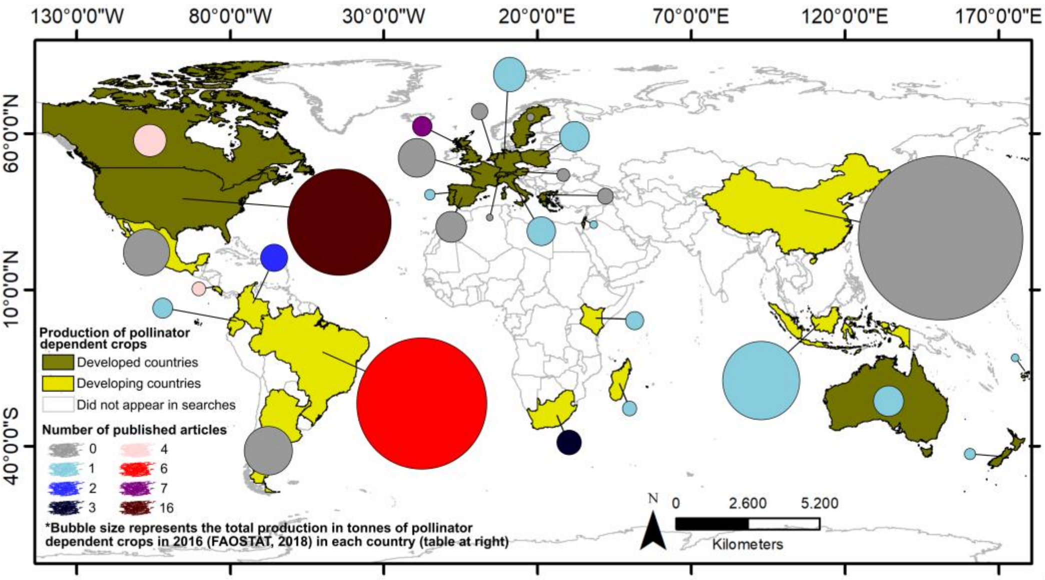
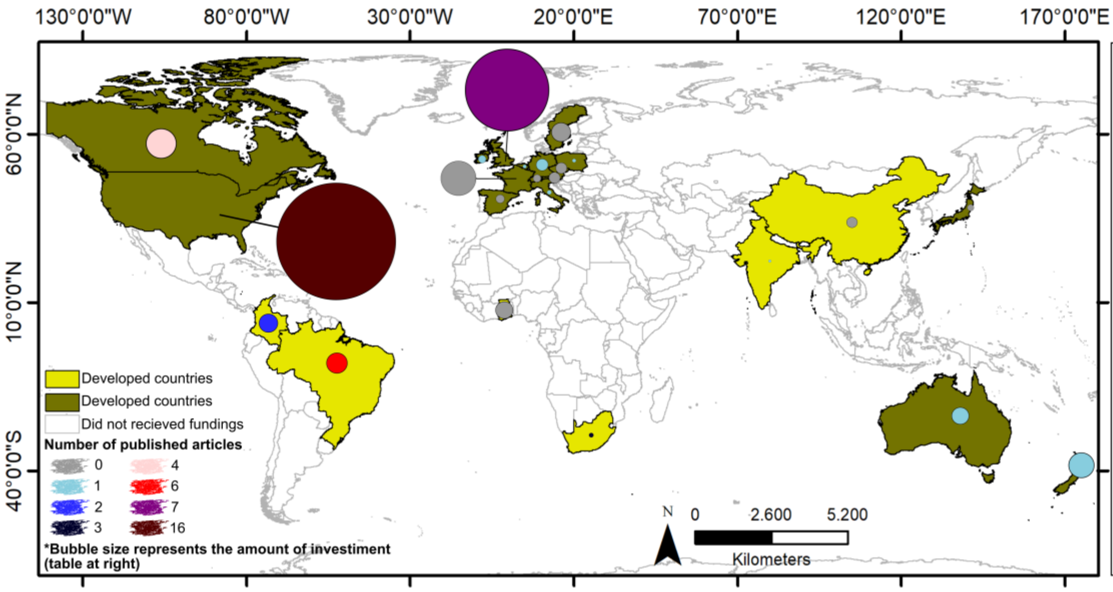


Fig. 6 Number of articles on the subject of pollination service valuation per journal until 2018. Search was made in the Web of Science with the argument "*pollinat* service** and *econ* val**". Our search returned a total of 177 articles, 100 of which explicitly focused on crop pollination services. Total number of journals: 62; the category "others" includes 49 journals, each of which with only one article.



Country	Production of pollinator dependent crops (tonnes)
Fiji	1,973,653
Switzerland	2,871,381
New Zealand	3,542,208
Israel	3,829,747
Sweden	4,156,770
Portugal	6,498,914
Austria	9,522,888
Costa Rica	12,531,627
Madagascar	13,133,041
Greece	15,233,830
Netherlands	16,681,963
Kenya	20,765,746
United Kingdom	23,423,466
Ecuador	23,896,604
South Africa	36,686,182
Italy	49,304,577
Poland	55,009,369
Spain	60,179,009
Australia	61,527,350
Colombia	65,492,621
Canada	66,252,327
Germany	68,780,660
France	87,948,129
Mexico	134,244,810
Argentina	148,357,072
Indonesia	364,677,581
United States	696,213,697
Brazil	1,032,885,154
China	1,658,171,076

Fig. 7 Distribution of agricultural production and research effort in countries that appeared in the scientometric survey in this study. Countries that produce any crop dependent on biotic pollination and appeared in our search are coloured in two categories: developed or developing economies according to the United Nations (2019) (N= 29 countries). Bubble size indicates the proportional production (tonnes) of all pollination-dependent crops in each country during the year of 2016 (according to the FAO database); values are informed in the box at right. Bubble color represents the number of published articles on economic valuation of pollination services by countries in which the studies were carried out (i.e. study area in the country) until December 2018 (Source: ISI Web of Science; https://www.webofknowledge.com). For the inclusion and exclusion criteria when searching articles at ISI Web of Science, please see the Flow diagram in Figure 1



Country	Fundings (x10⁶US$)
India	0.016
Poland	0.041
South Africa	0.049
Italy	0.053
Belgium	0.055
Japan	0.129
Ireland	0.207
Switzerland	0.234
Spain	0.237
China	0.375
Austria	0.431
Czech Republic	0.451
Germany	0.507
Australia	0.994
Ghana	1.069
Brazil	1.140
Colombia	1.233
Sweden	1.339
New Zealand	2.304
Canada	3.309
France	5.402
United Kingdom	25.505
United States	51.309

Fig. 8 Distribution of research funding and effort in countries that appeared in the scientometric survey in this study. Countries that received any research funding/grant and appeared in our search are coloured in two categories: developed or developing economies according to the United Nations (2019) (N= 23 countries). Bubble size indicates the amount of research funding in million dollars (US$). Bubble colour represents the number of published articles on the economic valuation of pollination services in countries with developed and developing economies until December 2018 (Source: ISI Web of Science; https://www.webofknowledge.com). Source for research funding/grants: Dimensions Platform (2018; https://www.dimensions.ai/). For the inclusion and exclusion criteria when searching articles at Web of Science, please see the Flow diagram in Figure 1

ECONOMIC VALUE OF FRUIT CROPS AND VULNERABILITY OF POLLINATION DECLINE IN BRAZIL

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ABSTRACT

Animal pollinators are in decline potentially leading to reduced pollination and hence production of animal-pollinated crops worldwide. However, it is still unclear how the consequences of pollinator shortages differ among regions. Here, we classified the dependence ratio, calculated economic gains attributed to animal pollination (EVP) to 29 fruit crops, as well as the vulnerability of pollinator decline in 3261 municipalities located in the Atlantic forest domain in Brazil. We used a bioeconomic approach, with data of biological reproduction and production value. In total, pollination services accounted for 7.04 (±0.003) billion BRL annually, which represents 24.6% of annual total economic value of those fruit crops production. States with highest EVP value was Bahia 1.92 (±0.01), Minas Gerais 1.91 (±0.006) and Espirito Santo 0.8 (±0.01). Orange (0.05 dependence index, *little dependent*) is the most common crop, produced by 1.791 municipalities and has EVP estimated by 0.16 billion BRL. However, Coffee (3.06 BRL billion, *moderate dependent*), Cocoa (1.22 billion BRL, *essentially dependent*), Apples (0.64 billion BRL, *highly dependent*), passion fruit (0.54 billion BRL, *essentially dependent*) and watermelon (0.27 billion BRL, *essentially dependent*), has the highest EVP values. The vulnerability of total area, which means the potential production value loss for the crops produced in Atlantic forest domain, in a pollinator decline scenario, is 28.6 percent. Pollination service has a great impact to the production of fruit commodities, but it is also an essential ecosystem service in many municipalities north to south of Brazil. Therefore, pollinator declines have the potential to impact agriculture of many municipalities, and lack of pollination could have negative consequences upon crop production, and therefore economy and food security.

Keywords*:* bioeconomic, crop pollinators, ecosystem service, fruticulture, valuation.

INTRODUCTION

Animal pollination plays a vital role not only as an ecosystem function in nature but also as an ecosystem service in an essential input to production of agricultural crops grown world-wide. Pollination services benefits around 75% of all leading global food crops and 37% of them are essentially or highly dependent of animal pollination (Klein *et al*., 2007). In general agriculture has become more pollinator-dependent and this tendency is more pronounced in the developing countries (Aizen *et al*., 2009),

The importance of animal pollination varies substantially between crops and therefore between regional economies (Bauer & Wing, 2016). Many of the world's most important yield crops benefit from animal pollination in terms of yield (Garibaldi *et al*., 2014; Hipólito *et al*., 2016; Pywell *et al*., 2015) and quality (Bartomeus *et al*., 2014; Garratt *et al*., 2014; Kasina *et al*., 2009; Klatt *et al*., 2014) including lead export products such as coffee and cocoa (Bravo-Monroy *et al*., 2015; Toledo-Hernández *et al*., 2017; Veddeler *et al*., 2008). The benefits that animal pollination brings to crop worldwide, is up to $577 billion annually and, in the last fifteen years, we see increases in producer prices for pollination dependent crops (Lautenbach *et al*.,2012). Aside from these monetary outcomes, pollinators also have important cultural value, acting as a source of inspiration in art, music and folklore (IPBES 2016).

However, pollination deficits have already been identified in several studies across world as consequence of habitat degradation and isolation from natural areas (Brosi *et al*., 2008; Carvalheiro *et al*., 2010; Haddad *et al*., 2015; Winfree *et al*., 2009; Xiao *et al*., 2016). Agriculture is a major driver of those disrupts through land use change, intensive practices such as tillage and agrochemical use (Dicks *et al*., 2016a; Potts *et al*., 2016). Still agriculture may also be an approach to provide opportunities to support wild pollinators, through ecological intensification (Bommarco *et al*., 2013; Hipólito *et al*., 2018) and support diversified farming systems (Kremen *et al*., 2012).

To this extent, there is a growing number of initiatives to measure pollination services to agriculture (Breeze *et al*., 2016; Hanley *et al*., 2015) and build sustainability strategies initiatives with their substantial intellectual and political influence on generated a great deal of scientific and media attention, elevating pollination into the public and political spotlight (Dicks *et al*., 2016b; Potts *et al*., 2016). However, considerate contextual differences between pollination and agriculture in the developed and developing worlds, is important to access local and regional aspects of pollination and crops production. Especially because across most of the developing world, there is limited formal knowledge of the distribution and abundance of important crop pollinators and little historical monitoring (Breeze *et al*., 2016; Timberlake & Morgan, 2018).

Recently studies in Brazil has shown that climate changes potentially could cause large impacts on crop production due to pollinator loss in almost 90% of all municipalities (Giannini *et al*., 2017) and therefor a scenario of pollination crises could cause a reduction of 13.5% – 41.59% in production of food derived from pollinator dependent crops, those impacts in monetary terms would be a reduce of US$ 4.86–14.56 billion per year (Novais *et al*., 2016). The decrease of Brazilian agricultural production will affect family farmers to large producers and affect all sectors of society, particularly the poor and the rural population. Those evidences confirmed the necessity of monitoring with standardized sampling in order to verify long-term trends in the population dynamics of pollinators and the vulnerability of pollination service.

In this context the objective of this paper is to assess the dependence of major fruit crops in Brazil, the economic value of pollinator service for those crops and which areas are most vulnerable to pollinator decline.

METHODOLOGY

Data. We collected the quantity, production value, area harvested and average yield of all the fruit crops in 2015, from the Brazilian Institute of Geography and Statistics (IBGE, http://www.sidra.ibge.gov.br/) produced in all municipalities in the Atlantic Forest domain (SOS Mata Atlântica & Inpe, 2015). (Figure1).

Dependence on pollinators. In order to determinate the crops (N=29) dependence of pollinators, we review data of the crops reproductive system in the literature. We considered only research that exhibited experiments on fruit set in natural pollination and total exclusion of pollinators. Using these data, we were able to accurately determine the real importance of animal pollination and classified according to Klein *et al*. (2007), in five classes: (1) essential; production is reduced by 90% or more when pollination services are lacking; (2) high: a reduction of 40% to 90%; (3) modest: a reduction of 10% to 40%; (4) little: a reduction of 0% to 10%; (5) no increase under conditions of animal-mediated pollination; and (7) unknown, when empirical studies are missing or inconclusive.

Economic value of pollination - EVP. Our database consisted of municipalities, fruit crops produced, the amount of production, agricultural land area and pollinators dependence, and so we calculate using a bioeconomic approach the economic contribution of pollination in each crop per area, i.e. economic value of pollination (EVP), as well as the overall vulnerability to pollinators decline (VPD) in areas from municipality level to national level (Gallai *et al*. 2009; Barfield *et al*., 2012).

We collected data of fruit production prices for each municipality in a country that has a substantial socioeconomical diversity, so geographical variation in prices of agricultural products are high. Consequently, applying a formula with the same price for a crop in every municipality would bring inaccuracy to the results. Here, we try to consider biological and socioeconomic variations for a more accurate value.

Although, pollination of other crops, such as tomato and pumpkin (Giannini *et al*., 2015), also have a high pollinator dependence, in this research we are only considering fruit crops. We consider this group of crops as a good proxy of the importance of pollinators in the country's economy, which is the third largest producer of fruit in the world. In addition, these crops have great importance in nutritional and food security for high nutritional value (Smith *et al*., 2015).

In the equation proposed by Gallai *et al*. (2009) and adapted by Barfield *et al*., (2012), where for each crop *i*, *i* € [1:*I*] (where *I* = 29 in this study), (Q*i*) is the quantity produced and (P*i*) is the price per unit, and *farm gate value* that represents the market value of a product multiplied by the weight of the product minus the selling costs, is calculated as:

$$EVP = \sum_{i=1}^{1} (P_i \times Q_i \times D_i)$$
$$= \sum_{i=1}^{1} (FGV_i \times D_i)$$

Unlike Barfield *et al*., (2012) we did not use the same price of a crop in every municipality, instead, we substitute the *farm gate value* (P*i* × Q*i*) by the *production value* (PV*i*) available in IBGE database that represents the price of production paid to producers in each area (municipality), which we consider a more accurate value for our approach:

$$EVP = \sum_{i=1}^{1} (PV_i \times D_i)$$

Crop vulnerability ratio - CRV. Adapting from Gallai *et al*. (2009), is the potential production value loss attributable to lack of pollinators, is calculated as the ratio of EVP to economic production value of an area (a) (municipality, estate and country), CRV can be stated as:

$$\mathrm{CRV} = \frac{\sum_{i=1}^{1}(PV_i \times D_i)}{\sum_{i=1}^{1}(PV_i)a}\,(\%)$$

$$\mathrm{CRV} = \frac{VEP}{PV} = \frac{\sum_{i=1}^{1}(P_i \times Q_i \times D_i)}{\sum_{i=1}^{1}(\mathrm{PV})a}$$

We also estimated the contribution of pollination to the total value of fruit production (PVFP):

$$PVFP = \frac{EVP}{TPV} = \frac{\sum_{i=1}^{1}(PV_i \times D_i)}{\mathrm{TPV}}\,(\%)$$

RESULTS

We registered production data of 29 fruit crops produced in 3261 municipalities in the Atlantic forest. According to fruit set experiments in the literature (appendix A, supplementary material), these crops were classified as essentially dependent on animal pollination (5-16.6%), highly dependent (8-26.6%), moderate dependent (5-16.6%), little dependent (9-30%) and non-dependent (2-6.67%). Cacao, passion fruit, quince, watermelon, and melon were the crops considered as essentially dependent on animal pollination (table 1).

Pollination services accounted for 7.04 (±0.003) billion BRL annually (2015) in Brazil fruit crops, which equals 24.6% of annual total economic value of those fruit crops production (PVFP). The states with highest EVP value are Bahia 1.92 BRL (±0.01), Minas Gerais 1.91 BRL (±0.006) and Espírito Santo 0.8 BRL (±0.01). Goiás had the lowest EVP value (0.0005 ± 0.0001). However, when we accounted for harvested area, EVP/km² was highest in Paraná (1.732,53 BRL/km²), São Paulo (1.048,40 BRL/km²) and Minas Gerais (1.021,89 BRL/km²) (table 2). When accounted for municipalities, highest EVP was in São Joaquim, Santa Catarina (0.15 billion BRL), Ilhéus, Bahia (0.12 billion BRL), Frainburgo, Santa Catarina (0.11 billion BRL), Livramento de Nossa Senhora, Bahia (0.05 billion BRL), Caxias do Sul, Rio Grande do Sul (0.05 billion BRL) and Canto do Buruti, Piauí (0.05 billion BRL) (appendix B, supplementary material).

Orange (*little dependent*) is the most common crop, produced by 1.791 municipalities and has EVP estimated by 0.16 billion BRL. However, coffee (3.06 BRL billion, *moderate*), cocoa (1.22 billion BRL, *essential*), apples (0.64 billion BRL, *high*), passion fruit (0.54 billion

BRL, *essential*) and watermelon (0.27 billion BRL, *essential*), had the highest EVP values. Together those crops represent 81,4% of total pollination economic services of all sampled crops.

Our total estimated CRV, which means the potential production value loss for the crops produced in the Atlantic forest domain, in a pollinator decline scenario, was 28.6 percent. The mean CRV highest values were in municipalities of Mato Grosso do Sul (0.442 ± 0.296), Bahia (0.356 ± 0.285), Piauí (0.344 ± 0.335), Ceará (0.315 ± 0.209) and Rio Grande do Norte (0.309 ± 0.255). A vulnerability ratio higher than 50% (> 0.47 CRV) was accounted for in 402 municipalities, of which 85 are in Bahia.

The GIS analysis of our results revealed patterns of spatial variation that are clear for EVP but less distinct for CVR. The analysis of our results reveals spatial intensity trends in EVP in southern Bahia, Espírito Santo, southern Minas Gerais and southern Santa Catarina (figure 2).

DISCUSSION

Local-specific estimates of variation in economic gains of animal pollination and their vulnerability to pollinators decline, together with information of pollinator-dependent fruit crops, spatial production, in this scope (73.288.863 ha of harvest area, in 3261 municipalities) were hitherto lacking for tropical and developing countries and as far as we know worldwide as well. Given that the economic valuation of ecosystem services is a key tool to facilitate the development of strategies and policies to conservation (Bauer & Wing, 2010; Gallai *et al*., 2009; Leonhardt *et al*., 2013), especially in Brazil, a highly pollination-depend country (Giannini *et al*., 2015; Lautenbach *et al*., 2012; Novais *et al*., 2016), with an expected pollinators decline due to climate change (Giannini *et al*., 2017) or degradation of natural habitat (Ribeiro *et al*., 2009) this assessment is of interest to policy and the entire society. As we expect, 43,2% of fruit crops are essentially or highly dependent on animal pollination and another 46,6% somehow benefit from pollinator visits, and this services account for more than 7.0 billion BRL. These economic gains are most pronounced in municipalities with coffee and cocoa intensified production (together accounted for 60,8% of total EVP). In the spatial analysis, the main intersection hotspot between EVP and CRV is in southern Bahia, area of greatest production of Cocoa in Brazil. This crop emphasizes the importance of pollinators in the agricultural economy, due to pollinator essential dependence and an extremely high production value that exceeds 1.1 billion BRL.

Our findings corroborate with recent studies that indicate that Brazilian agriculture is highly dependent on the pollination services (Giannini *et al.,* 2015; Lautenbach *et al.,* 2012) and in a scenario of pollinators decline, production losses of commodities (e.g. orange, coffee, cocoa) would affect Brazilian GDP (Giannini *et al.,* 2017; Novais *et al.,* 2016). With the exception of cocoa and coffee (produced mainly in Minas Gerais e Bahia), most of the dependent-crops are produced in municipalities scattered throughout Brazil, and thus distribution of high vulnerability areas is widespread from north to south. For instance, watermelon and passion fruit are both profitable and essentially dependent crops, cultivated in all states (except for Goias) and, therefore, lift up the CRV value of the cultivated area. In fact, cultivated areas of passion fruit have shown already true pollen limitation in productivity and, therefore, farmers often pollinate flowers by hand (Bos *et al*., 2007). Our CRV results can also be interpreted as areas of potentially production increase by introducing managed bees, when applicable (Isaacs *et al.,* 2017). Moreover, those areas are potentially suitable for ecological intensification of agriculture, that could raise quantity and quality and, consequently, crops production value, through pollinators friendly-practices (Hipólito *et al.,* 2016; Kovács-Hostyánszki *et al.,* 2017; Pywell *et al.,* 2015).

We observed a much higher EVP value for fruit commodities, mainly due to production value and the amount of production for foreign trade (orange, coffee, cocoa). However, perhaps a more important benefit of pollination to agriculture is the impact locally economy and food security throughout Brazil. Widespread high CRV values, can suggest that measures of economic pollination benefits may not be accessible only through the economics contribution to crop production (EVP), but also by the set of locally grown crops and their dependence on animal pollination. Specially because we potentially face important decreases in the pollinator occurrence in some municipalities with the highest value of production (Giannini *et al.,* 2012; Giannini *et al.,* 2017)

We recognize a few bias in this study, but they certainly do not compromise the general trends that we found. Some part of fruit crops production measured in this study are commercialized in informal market, so productivity and production value here not fully monitored and accounted. Also, other crops cultivated or collected in an extractive (except 4 crops) manner were not considered in our research for lack of data in the IBGE database. Nevertheless, this data shortage can only indicate that economic benefits and vulnerability values of Brazilian fruit crops are probably much higher than we estimated.

FINAL CONSIDERATIONS

We have attempted to access the importance of pollinators in fruit production and consequent economic gain productions, at a local scale in an agrobiodiverse country. Through a bioeconomic approach, we found that pollination contributes to the production of fruit commodities, but it is also an essential ecosystem service in many municipalities north cost to south of Brazil. Therefore, pollinator declines have the potential to impact agriculture of many municipalities, and lack of pollination could have consequences upon crop production, and therefor economy and food security.

The Brazilian agrobiodiversity is enormous and future studies should access interactions and dependencies on pollinators in these crops. We emphasize the huge lack of pollination ecology data for many species of crops grown in Brazil (Giannini *et al.*, 2015). Field experiment data are extremely necessary to access the effects of land use, pesticide and climate change in multiple spatial scales, the revenue to a suitable pollination service and its consequences on the ecological functions, economy and food security of society.

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Table 1. Crops name, Index of dependence on pollinators, dependence on pollinators, economic value of pollination serviced (R$), economic value of pollination service (R$) per harvested area ($km^2$), crop production value (R$) (source: ibge), number of municipalities and production type (of all fruit crop produced) in municipalities located in the Atlantic forest domain.

Crops	Index of Dependence on Pollinators	Dependence on Pollinators	Economic value of pollination serviced (R$)	Economic value of pollination service (R$) / harvested area ($Km^2$)	Crop production value (R$) (source: IBGE)	Number of municipalities	Production type
Cocoa	0.95	essential	1218894650	0.27	1283047000	150	cultivated
Passion Fruit	0.95	essential	538339350	2.27	566673000	715	cultivated
Quince	0.95	essential	430350	0.64	453000	8	cultivated
Watermelon	0.95	essential	271711400	0.88	286012000	853	cultivated
Melon	0.95	essential	75466100	0.6	79438000	395	cultivated
Avocado	0.65	high	96756400	1.05	148856000	492	cultivated
Coquilho	0.65	high	716300	-	1102000	8	extractivism
Guarana	0.65	high	11165050	0.2	17177000	17	cultivated
Apple	0.65	high	643467500	1.61	989950000	185	cultivated
Mango	0.65	high	225737200	0.79	347288000	637	cultivated
Mangaba	0.65	high	218400	-	336000	16	extractivism
Pear	0.65	high	17876300	0.7	27502000	274	cultivated
Peach	0.65	high	124242300	0.86	191142000	657	cultivated
Babaçu	0.05	little	127100	-	2542000	11	extractivism
Banana	0.05	little	176824300	0.06	3536486000	1750	cultivated
Khaki	0.05	little	10562150	0.07	211243000	535	cultivated
Palm	0.05	little	2347200	0	46944000	27	cultivated
Orange	0.05	little	165634250	0.04	3312685000	1791	cultivated
Lemon	0.05	little	29903600	0.06	598072000	886	cultivated
Papaya	0.05	little	48753400	0.13	975068000	364	cultivated
Mandarine	0.05	little	28178200	0.05	563564000	1037	cultivated
Umbu	0.05	little	116550	-	2331000	69	extractivism
Coffee	0.25	moderate	3063901750	0.17	12255607000	1070	cultivated
Coconut	0.25	moderate	224034500	0.18	896138000	774	cultivated
Fig	0.25	moderate	15845750	0.27	63383000	366	cultivated
Guava	0.25	moderate	48519500	0.52	194078000	465	cultivated
Pequi	0.25	moderate	1793000	-	7172000	64	extractivism
Pineapple	0	non-dependent	-	0	1004905000	416	cultivated
Grape	0	non-dependent	-	0	977408000	1011	cultivated

Table 2. States names, economic value of pollination service (EVP), Vulnerability ratio (CRV) and Production value of fruit crops produced in municipalities located in the Atlantic forest domain in each state.

State	Production value (R$) (source: IBGE)	EVP (R$)	CRV (%)
Alagoas	209.225.000,00	24.077.100,00	24
Bahia	4.860.668.000,00	1.929.767.850,00	32
Ceara	433.027.000,00	151.663.850,00	30
Espirito Santo	3.793.598.000,00	896.430.150,00	30
Goiás	10.951.000,00	467.100,00	06
Mato Grosso do Sul	32.593.000,00	16.569.600,00	37
Minas Gerais	8.461.633.000,00	1.908.803.550,00	24
Paraíba	366.798.000,00	21.639.700,00	33
Paraná	1.628.523.000,00	330.983.850,00	33
Pernambuco	130.177.000,00	12.527.200,00	24
Piauí	67.201.000,00	59.279.150,00	31
Rio de Janeiro	532.358.000,00	59.217.950,00	20
Rio Grande do Norte	187.704.000,00	25.871.400,00	33
Rio Grande do Sul	735.963.000,00	234.004.600,00	35
Santa Catarina	1.250.079.000,00	565.684.700,00	29
São Paulo	5.439.505.000,00	716.080.350,00	26
Sergipe	446.599.000,00	88.494.450,00	25
Total	28.586.602.000,00	7.041.562.550,00	30

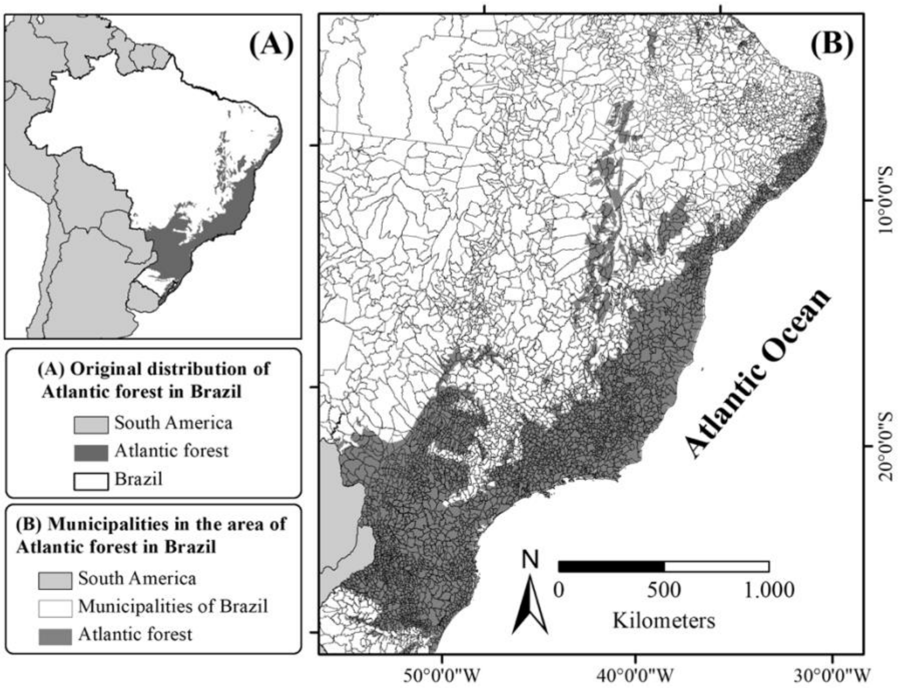

Figure 1. (A) Original distribution of the Brazilian Atlantic forest region, (B) Municipalities in the area of Atlantic forest in Brazil, in gray municipalities sampled. (source: SOS Mata Atlântica/INPE, 2015).

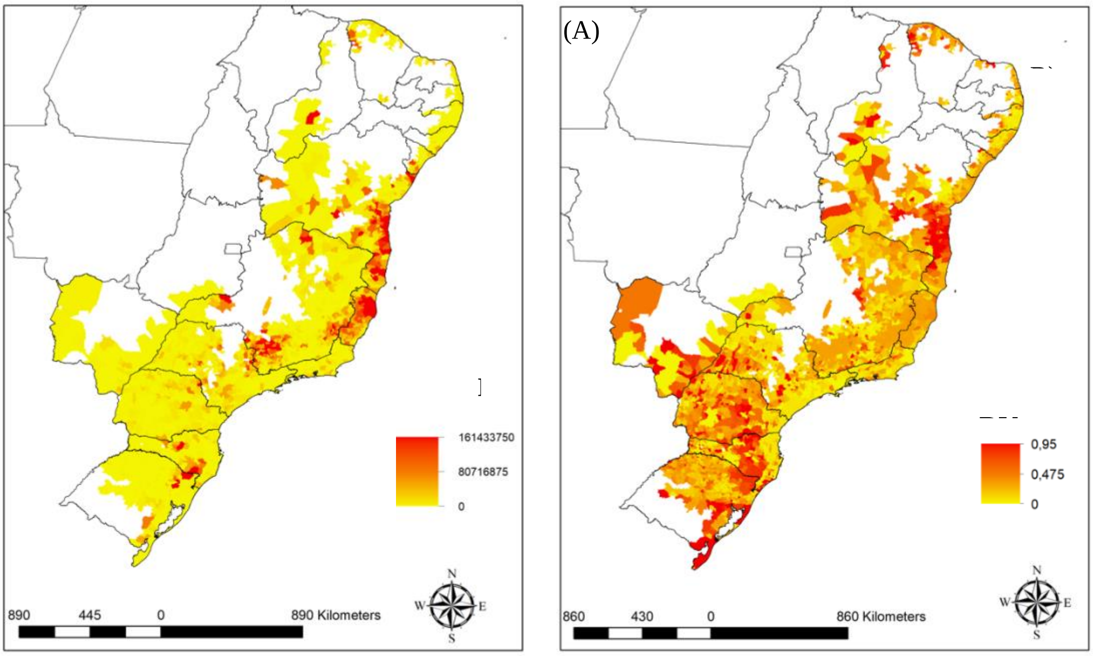

Figure 2. Geographic Information System (GIS) analyses of (A) economic value of pollination (EVP) of municipalities and (B) crop production vulnerability to pollinators decline in all municipalities of the Atlantic forest domain.

POLLINATOR DEPENDENT CROPS ACCOUNTS FOR A SUBSTANTIAL PORTION OF MOST NUTRITIONAL COMPONENTS WHEN COMPARED TO NON-DEPENDENT CROPS

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ABSTRACT

Pollination service is a source of multiple benefits to people and measures of animal pollination outcomes are increasingly explored and brought to public and political awareness. Pollinators contribute to agricultural yield for an estimated 35% of global food production and are directly responsible for up to 40% of the world's supply of some micronutrients, such as vitamin A. Few studies have attempted to link the loss of pollinator-related foods to health outcomes. Here, we examine if there is a group of nutrient components that are directly linked to pollinator dependent crops and how the nutritional components are distributed through pollinator dependent (PD) and non-dependent (ND) crops. We assessed the water and nutrient content of the 40 main fruit crops produced in Brazil. Our results suggest a group trend of pollinator dependent crops related to water and nutritional content, in Brazilian leading crops. Higher content of water in the fruits and seeds is the main vector for this cluster. We found that fruits and seeds of PD crops form a group of high water concentration fruit and seeds and share an extremely high concentration of lipids, vitamin A, vitamin B1, vitamin B2 (riboflavin), vitamin B9 (folate), vitamin C and vitamin E (α-tocopherol) supply. This is the first study to relate fruit and seeds water content and vitamin B1 to pollination services, a continuous needed micronutrient is humans' diet. We discuss the nutrients supply and the health outcomes associated with the possible decreased of pollination service, concluding that pollinators decrease could drastically impact the Brazilian human diet, heath and the food security.

Keywords: Animal-mediated pollination, agriculture, nutritional value, vitamin A, Brazilian crops

INTRODUCTION

Pollinators are linked to human well-being through the maintenance of ecosystem health and function, wild plant reproduction, crop production and food security (Potts et al., 2016). The benefits provided by pollination service to human's food supply reached recently international focus. Pollinator benefits are being increasingly explored in the literature and brought to public and political awareness (Dicks et al., 2016; Potts et al., 2016).

Animal pollination impact in yield and/or quality of approximately 75% of globally important crop types, including most fruits, seeds and nuts and several high-value commodity crops such as orange, coffee and cocoa. The economic value from animal pollination services to agriculture was estimated to be $235-577 billion US$ in 2015 (Lautenbach et al., 2012). Pollination service is responsible for 81 million hives annually produce 65,000 tones of beeswax and also contribute directly to medicines, biofuels, fibers, construction materials, musical instruments, literature, religion and technology (Potts et al., 2016).

Another key benefits from animal pollination is the impact on human diet and food security. Previous studies has shown that crop plants that depend fully or partially on animal pollinators contain more than 90% of vitamin C, most of lycopene, the antioxidants beta-cryptoxanthin and beta-tocopherol, vitamin A and related carotenoids, calcium and fluoride, and a large portion of folic acid available worldwide (Eilers et al., 2011; Ellis et al., 2015; Ghosh and Jung, 2018; Smith et al., 2015). Those nutrients are essential to humans diet and nutritional deficiency in a pollinators crisis is expected to affect more than 1 in 4 people around the globe (Ellis et al., 2015). For example, deficiency of vitamin A carries concerning public health implications, causing 20–24% of child mortality from measles, diarrhea and malaria and 20% of all maternal mortality (Smith et al., 2015).

In this study we investigate how nutritional components are distributed in pollinators dependent and non-dependent crops, including water content and energy. We explored the importance of pollination service in the set of nutritional components of the human diet, and therefore, the consequences of a pollinator crisis in human diet and health.

METHODOLOGY

Data. We collected data of nutritional components of 46 leading crops produced in brazil (IBGE, 2018) from the TBCA 2018 (Brazilian food composition table) and USDA 2019 (U.S. Department of Agriculture). We consider only crops that fruit or seeds are the consumed parts (table 1). Crops were classified according to their reproductive dependence on pollinators as pollinator dependent (PD) when a lack of pollinator service cause the reduce of fruit and seeds production at some level, essentially (more them 90%), highly (40% to 90%;), modest (10% to 40%) and non-dependent (ND) when the absence of pollinators impact up to 10% of fruits set (little) or if doesn't affect the fruit and seed set (Klein et al., 2007).

Statistics analyses. To test for differences in nutritional components between the two crop groups, pollinators dependent and non-dependent crops, we conducted a principal component analysis (PCA) of all nutritional components. We additionally run a T test to compare each components concentration of the two groups. All statistical procedures were done with R Development Core Team 2014. We also calculated the proportion of nutrients in both groups.

RESULTS AND DISCUSSION

We categorized the 46 main fruit crops produced in Brazil as 25 crops as ND (pollinators non-dependent crops) and 21 as PD (pollinator dependent crops). The principal component analysis (PCA) reveals that nutritional composition varies by 51.09% between the PD and ND crops groups (PC1 - 37,21% and PC2 - 13,99%) (figure 1). The t test shown that statistically only niacin contend is higher in ND crops ($t = 2.666$, $df = 34.214$, $p = 0.01164$), others nutritional components have shown no statistical difference between ND and PD group (figure 2).

Our results suggest a group trend of pollinator dependent crops related to water and nutritional content, in Brazilian leading crops. Higher content of water in the fruits and seeds is the main vector for this cluster. In PD crops, there is also a higher concentration of fat, vitamin A, vitamin B1 (thiamin), vitamin B2 (riboflavin), vitamin B9 (folate), vitamin C (ascorbic acid), vitamin E (□-tocopherol) and calcium. Whereas ND crops have higher quantity of carbohydrates, vitamins B3 (niacin), B6 and K (phylloquinone).

Our findings reinforce the hypothesis that a pollinator crisis could lead to a nutrient shortage to human health (Eilers et al., 2011; Smith et al., 2015). Almost all macronutrients (with the exception of carbohydrates) are much higher concentrated in PD crops. Globally, around 74% of all produced lipids are present in oils from plants that are pollinated by animals (Eilers et al., 2011). According to our estimates, in leading fruit and seed crops in Brazil, 87.66% of fat is provided by PD crops and the monounsaturated fatty acids is up to 82.77%. Nuts (coconut, cashew nut and groundnut) sunflower and oil palm are the main source of fat compounds and they, at some level, beneficiate from pollinators service. Of all the macronutrients, saturated fatty acids have the greatest potential to cause disease states such as elevated cholesterol levels, when consumed in excess amounts. Reducing fatty acids in the diet is, therefore, important for weight control and proper functioning of the immune system, which might not just fight infections but could also strengthen the type of immune cells to fight tumor cells (Obi, 2015). However, the coconut oil, considered the healthiest of all dietary oils (Baeza-Jiménez et al., 2017), have potential to enhance the anti-obesity response (Hargrave et al., 2005) and affect nutrition-related chronic diseases (FAO, 2010). The overall consensus is to increasingly replace saturated fatty acids with monounsaturated fatty acids as part of a healthy lifestyle diet and this change should include fruits and vegetables as main source of fat (FAO, 2010).

It seems that animal pollinated crops also are very important contributors of minerals in the human diet (Eilers et al., 2011). It was estimated that 58% of calcium and 29% of iron come from pollinator dependent crops with 9% and 6% respectively, attributed solely to animal pollination (Ellis et al., 2015). Our results demonstrated a relative balance in minerals between PD and PN crops produced in Brazil, but concentrations of calcium, potassium and zinc from PD crops are much higher than we expected. The relative proportion calculated based on the average means of each group showed 65% of calcium in ND crops and 34% in PD crops. However, the proportions based on total amount show 81.44% associated with PD crops and 18.54% with the ND crops. These differences between proportions of averages and total amount are due to the high variation of the values between the crops (i.e. high standard deviation). Relatively many ND crops provide calcium but with low concentrations (olive - 45.7mg, oat - 47.9mg and rice - 57.7mg) while PD crops offer extremely higher values in their fruits and seeds than any ND crops (bean - 107mg, sunflower - 133mg, orange - 161mg and soybean - 204mg,). The maintenance of calcium concentrations in extracellular fluids is of extreme importance, since calcium is involved in numerous functions such as regulation of heart rate, blood coagulation, secretion of hormones, bone formation and maintenance, tooth development and healthy functioning of the nervous system and muscles (FAO, 2013). However, calcium sources are almost always animal related (like dairy products) because they are more bioavailable than vegetable sources. However, dairy production is costly and environmentally inefficient, and consumption is not culturally viable in many countries (Eilers et al., 2011).

Almost all crops, regardless pollinator dependence, have similar sodium and potassium values, with the exception of olive with high content of sodium. Higher proportion in total value of PD crop group is probably due to a larger number of crops in this group. With the increasing consumption of processed food, which has, most populations around the world are consuming sodium at levels exceeding physiological needs and current recommendations. As sodium consumption rises, increased consumption of potassium may be even more beneficial because, in addition to other benefits, it can mitigate the negative effects of elevated sodium consumption on blood pressure and cardiovascular disease. There has been a large decrease in potassium intake which now, in most developed countries, averages around 70 mmol day−1, i.e. only one third of our evolutionary intake (WHO, 2014, 2012). It is proven that the best way to increase potassium intake is to increase the consumption of fruits and vegetables, since potassium is commonly withdrawn from processed foods (He and MacGregor, 2008).

The deficiency of micronutrients, specially vitamins, affects individuals of all age and gender and can increased incidence of a variety of chronic and infectious diseases (Ellis et al., 2015). The hidden hunger is one of the most urges of global development today, especially in developing and poor countries are estimated to affect more than 1 in 4 people around the globe (Tulchinsky, 2010). Vitamins are the main micronutrient, so far, related to animal-pollinated crops (Brittain et al., 2014; Chaplin-Kramer et al., 2014; Eilers et al., 2011; Ghosh and Jung, 2018; Smith et al., 2015). Our results followed the literature trend, showing vitamins as the most important micronutrients related to pollination service (Eilers et al., 2011; Smith et al., 2015). Analysis of the contribution of pollination to human health through diet, specifically examining vitamin A and B9, showed that the complete removal of pollinators could lead to approximately 71 million people, in low-income countries, newly deficient in vitamin A, leading to chronic and mal nutrition related disease. Vitamin B9 are extremely important in children's diet and is also a critical nutrient for pre-natal nutrition and is therefore a concern for pregnant women (Ellis et al., 2015). Already 2 billion people in central Africa and southern and southeast Asia, has vitamin A supplies below the average requirement generally (Smith et al., 2015). The same losses of animal pollinators would place an additional 173 million people at risk for vitamin B9 (folate) deficiency (Smith et al., 2015).

Although vitamin have been previously related to animal pollinated crops, specially vitamin A, C and B complex, in general our estimated are much higher than we expected. We showed that up to 95% of vitamin A is produced by animal pollinated crops (manly in mango, passion fruit and melon) and regardless the proportion data, percentage of average (99.29%) or total value (99.49%) vitamin B1(thiamin) is also almost exclusively provided by PD crops. This is the first study to relate B1 content and pollination services. B1 is continuous need in supply humans diet, because it is not stored in the body (NAS, 1998). It should be part of the daily diet, the absence causes the deficiency disease called beriberi, which has been known since antiquity. More recently, at least in industrialized nations, thiamin deficiency has been mainly found in association with chronic alcoholism, where it presents as the Wernicke-Korsakoff syndrome (NAS, 1998). Vitamin B1 helps prevent complications in the nervous system, brain, muscles, heart, stomach, and intestines. It is also involved in the flow of electrolytes into and out of muscle and nerve cells. Heating, cooking, and processing foods, and boiling them in water, destroy thiamin. As vitamin B1 is water-soluble, it dissolves into cooking water, making it more important to obtain from the consumption of raw fruits and vegetables (NAS, 1998).

More than 97% of vitamin C produced by leading Brazilian crops, also comes mainly from animal pollinators plants. Vitamin C is abundant in several dependent crops namely guava, cashew, coffee, papaya, orange and lemon. Eilers et al. (2011) found 98% of the available vitamin C produced by to pollinators dependent crops, primary citrus and other fruits and vegetables. The antioxidant role of vitamin C, along with vitamin E and □-carotene, is well recognized. Although nowadays is not that common, lack of vitamin C in the diet can cause scurvy, particularly between elderly and chronic alcoholics.

It is increasingly clear, a trend of production of nutrients related to pollinators. However, studies relating the contend of nutrients and pollination to specific crops and nutrient contends are very scarce. Experiments suggest that pollination could have unexpected effects on crop nutrition and influence the ratio of nutrients (fat and vitamin E) that are important for human health due to interactions with other inputs, such as reduced water and no fertilizer (Brittain et al., 2014). In Braeburn apples (Malus domestica Borkh) fruit set poor pollination had no effect on Mg and K concentrations, but can reduce Ca concentrations in early stages of bloom (Volz et al., 1996). It has also been shown that oil content in rapeseed (Brassica napus var. SW StratosTM) was improved by pollination, as well as seed weight per plant at 18% (Bommarco et al., 2012), and those effects of insect pollination are related to quality parameters leading to better market price.

Evidences that pollinators dependent crops produce higher concentration of some nutritional components, particularly lipids and vitamins, makes this ecosystem service, crucial to a heath human diet. Therefore, if pollinators do contribute to nutritional health, continued declines of pollinator populations could have drastic consequences for public health. In Brazil around 60% major food crops in Brazil depend to some degree on animals for pollination (Giannini et al., 2015; Novais et al., 2016). Recently, a projected climate change assessment considering the geographic distribution of 95 pollinator species of 13 Brazilian leading crops, predicted that almost 90% of the municipalities analyzed will face the disruption of co-occurrence of crops and they pollinators (Giannini et al., 2017). Furthermore, it is known that pollinators dependent crops are directly affected by changes in landscape (Ricketts et al., 2008; Zou et al., 2017) and distance from natural habitats lead to significant exponential declines in the richness of pollinators, rate of visitation on crops (Potts et al., 2016) and consequently disruption of the pollination ecosystem service.

FINAL CONSIDERATIONS

We used nutrient data of the leading Brazilian crops to investigate how nutritional components are scattered in pollinators dependent and non-dependent crops. This study provides the first evaluation of fruit and seeds contents related to pollinators dependent and non-dependent crops, that including water content and energy supply. We found that fruits and seeds of PD crops form a group of high water concentration fruit and seeds and share an extremely high concentration of lipids, vitamin A, vitamin B, vitamin B2 (riboflavin), vitamin B9 (folate), vitamin C and vitamin E (□-tocopherol) supply and therefore pollinators decrease could drastically impact the Brazilian human diet, heath and the food security.

The results relating nutrients to pollinator dependent crops is higher than we expected in number and content of nutrients. We believe that, due to the high values of standard deviation, proportions using total value of nutrients content, instead of using average means, in our study, appears to be more effective to highlight the importance of pollinators to human diet and health. Often content and concentration of nutrients between crops vary highly, regardless the dependence, within and between the two groups. As our intention was to compare the nutritional contribution in the group of crops that benefits from pollinator as a whole, and thus the importance of the pollination service, the approach using the sum of values in each group seems to be more realistic. We recognize a bias in these estimates because the number of NP cultures is less than the number of PD cultures (respectively 11 and 29). Our sampling consists of the leading crops produced and, consequently, more consumed by the Brazilian population, therefore, reflects the set of crops and nutrient supply in people's diet. It is known that DN crops are more produced in quantity than PD, while PDs are much more numerous and nutritionally diverse (Lautenbach et al., 2012; Schulp et al., 2014), the results presented here only corroborate with this statement. We hope to take a step forward in order to raise awareness that biodiversity conservation and the encouragement of more sustainable agricultural practices (Hipólito et al., 2018; Kremen et al., 2012), through the ecological intensification of agriculture (Kovács-Hostyánszki et al., 2017; Lichtenberg et al., 2017), generate win-win scenarios, including benefits to human well-being through health and diversify human diet (Potts et al., 2016).

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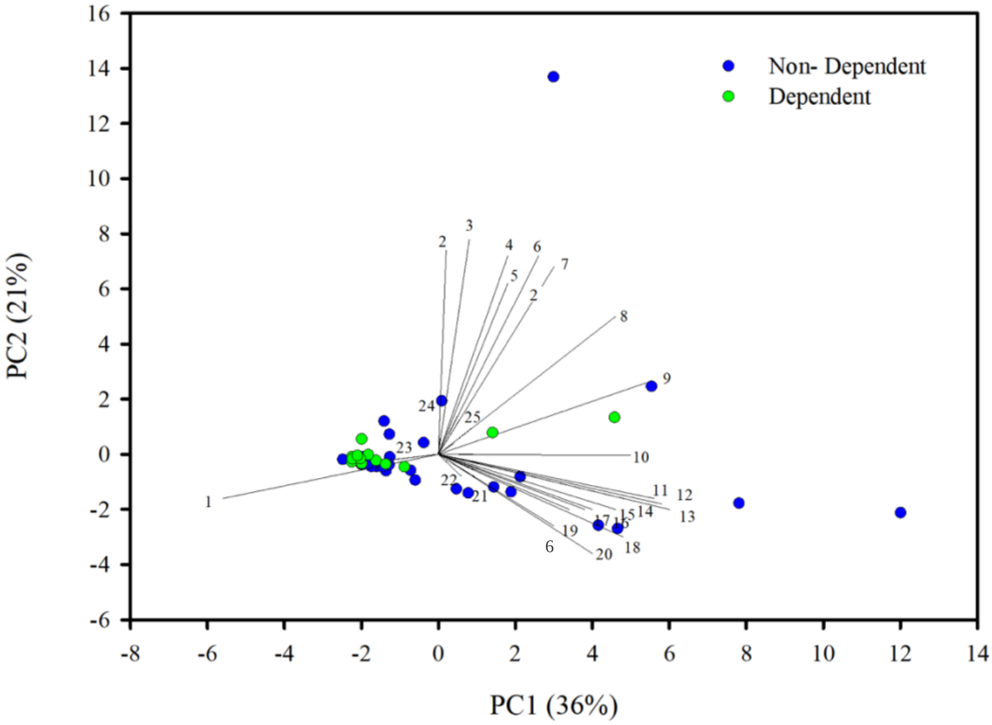

Water	1	Calcium	26	Vitamin C	23
Energy	9	Iron	13	Vitamin B1	25
Protein	15	Magnesium	11	Vitamin B2	17
Carbohydrate	20	Phosphorus	12	Vitamin B3	10
Fiber	19	Potassium	18	Vitamin B6	16
Lipids	6	Sodium	24	Vitamin B9	21
Fat saturated	4	Zinc	14	Vitamin A	3
Fat monounsaturated	7			Vitamin E	5
Fat polyunsaturated	8			Vitamin K	22

Figure 1. Principal component analysis (PCA) of dependent and non-dependent crops, using the nutritional components as variables. PC1 and PC2 explained 57% of variation from fruit crops nutritional components.

Table 1. List of the 40 main crops produced in Brazil whose fruits or seeds are the consumed parts. Source of information on the dependence of pollinators are Campbell et al., 2018[1]; Giannini et al., 2015[2] and Klein et al., 2007[3] .

Crop	Scientific name	Pollinator Dependence
Avocado	*Persea americana* (Mill.)	PD - great[2]
Pineapple	*Ananas comosus* ((L.) Merr.)	ND - non-dependent[2]
Assai	*Euterpe oleracea* (Mart.)	PD - modest[1]
Groundnut	*Arachis hypogaea* (L.)	PD - little[3]
Rice	*Oryza* spp.	ND - non-dependent[3]
Oat	*Avena sativa* (L.)	ND - non-dependent[3]
Olive	*Olea europaea* (L.)	ND - non-dependent[3]
Banana	*Musa paradisiaca* (L.)	ND - non-dependent[2]
Cacao	*Theobroma cacao* (L.)	PD - essential[2]
Coffee	*Coffea arabica* (L.)	PD - modest[2]
Cashew	*Anacardium occidentale* (L.)	PD - great[3]
Persimmon	*Diospyros kaki* L.f.	PD - little[3]
Cashew nut	*Anacardium occidentale* (L.)	PD - great[3]
Rye	*Secale cereal* (L.)	ND - non-dependent[3]
Barley	*Hordeum vulgare* (L.)	ND - non-dependent[3]
Coconut	*Cocos nucifera* (L.)	PD - modest[3]
Oil palm	*Elaeis guineensis* (L.)	PD - little[2]
Cow peas	*Vigna unguiculata* ((L.) Walp.)	PD - little[3]
Broad bean	*Vicia faba* (L.)	PD - modest[3]
Bean	Phaseolus sp.	PD - little[2]
Fig	*Ficus carica* (L.)	PD - modest[3]
Sunflower	*Helianthus annuus* (L.)	PD - great[2]
Guava	*Psidium guajava* (L.)	PD - great[2]
Orange	*Citrus aurantium* (L.)	PD - little[3]
Lemon	*Citrus latifolia* Tanaka	PD - little[3]
Apple	*Pyrus malus* (L.)	PD - great[3]
Papaya	*Carica papaya* (L.)	PD - little[3]
Mango	*Mangifera indica* (L.)	PD - great[3]
Passion fruit	*Passiflora edulis* (Sims)	PD - essential[2]
Watermelon	*Citrullus lanatus* (Citrullus)	PD - essential[2]
Melon	*Cucumis melo* (L.)	PD - essential[2]
Corn	*Zea mays* (L.)	ND - non-dependent[3]
Pear	*Pyrus communis* (L.)	PD - great[3]
Peach	*Prunus persica* ((L.) Stokes)	PD - great[3]
Soybean	*Glycine max* ((L.) Merr.)	PD - modest[3]
Mandarin	*Citrus reticulata* (Blanco)	PD - little[3]
Tomato	*Lycopersicon esculentum* (Mill.)	PD - great[2]
Grape	*Vitis* spp.	ND - non-dependent[3]
Wheat	*Triticum* spp.	ND - non-dependent[3]
Sorghum	*Sorghum bicolor* (L.) Moench	ND - non-dependent[3]

Table 2. Means (value/100g), standard deviation (SD), proportion (a%) of average means and total value means (%tv) of water, energy and nutrients derived from pollinators dependent (PD) and non-dependent (ND) crops.

Nutritional Component	**PD (Mean ± SD)**	**ND (Mean ± SD)**	**PD (%a)**	**ND (%a)**	**PD (%tv)**	**ND (%tv)**	**W**	**P**
WATER (mg)	73.2 ± 30.6	52.6 ± 35.04	**58.19**	**41.81**	**78.22**	21.78	374	**0.02**
ENERGY (kcal)	153.5±203.7	278.4 ± 322.02	35.54	64.36	58.87	41.13	222.5	**0.04**
MACRONUTRIENTS								
Protein (g)	3.6 ± 6.5	7.3 ± 10.2	33.03	66.97	72.56	27.44	256	0.29
Carbohydrate (g)	13.7 ± 7.6	29 ± 25.35	32.08	76.92	51.14	48.86	228.5	0.07
Fiber (g)	3.5 ± 3.3	6.32 ± 5.9	35.64	64.36	69.81	30.19	239.5	0.13
Total lipid (g)	8.1 ± 16.9	10.05 ± 21.9	44.63	55.37	**87.66**	12.34	252	0.24
Fatty acids, saturated (mg)	1104.8 ± 2371.2	3479.3 ± 9815.3	24.10	75.89	**91.02**	8.98	238.5	0.12
Fatty acids, monounsaturated (mg)	2437.9 ± 6674.6	3565.6 ± 8879.5	40.61	59.39	**82.77**	17.23	237.5	0.11
Fatty acids, polyunsaturated (mg)	781.2 ± 2087.7	2304.6 ± 4803.8	25.32	74.68	**80.52**	19.48	243	0.16
MINERALS								
Calcium (mg)	21.9 ± 33.2	42.4 ± 49.5	34.06	65.94	**81.44**	18.56	218.5	**0.03**
Iron (mg)	1.2 ± 2.2	2.72 ± 4.37	30.61	69.39	59.49	40.51	225.5	0.05
Magnesium (mg)	33.6 ± 74.1	83.58 ± 154.32	28.67	71.33	49.09	50.91	222.5	0.04
Phosphorus (mg)	62.9 ± 153.6	185.25 ± 337.39	25.35	74.64	49.05	50.95	227.5	0.06
Potassium (mg)	236.9 ± 182.5	476.14 ± 520.6	33.22	66.78	70.13	29.87	242.5	0.15
Sodium (mg)	91.1 ± 319.2	57.27 ± 258.11	**61.40**	38.60	49.11	50.89	264.5	0.41
Zinc (mg)	0.59 ± 1.5	1.31 ± 1.64	31.05	68.95	63.48	36.52	248.5	0.21
VITAMINS								
Vitamin C, ascorbic acid (mg)	47.75 ± 83.86	52.67 ± 35.04	47.55	52.45	**97.11**	2.89	351.5	0.11
Vitamin B1, Thiamin (mg)	23.85 ± 88.9	0.17 ± 0.24	**99.29**	0.71	**99.49**	0.51	268.5	0.48
Vitamin B2, Riboflavin (mg)	0.03 ± 0.04	0.1 ± 0.19	23.08	76.92	**74.62**	25.38	242	0.19
Vitamin B3, Niacin (mg)	0.6 ± 0.5	3.11 ± 6.8	16.17	83.83	43.44	56.56	253.5	0.26
Vitamin B6 (mg)	0.09 ± 0.11	0.33 ± 0.78	21.43	78.57	40.64	59.36	229.5	0.07
Vitamin B9, Folate, DFE (mg)	0.01 ± 0.02	0.07 ± 0.13	12.50	87.50	**84.83**	15.17	231	0.08
Vitamin A (mg)	0.43 ± 0.009	0.05 ± 0.06	10.55	89.44	**95.70**	4.30	343	0.17
Vitamin E (alpha-tocopherol) (mg)	0.0004 ± 0.0005	0.002 ± 0.004	16.67	83.33	**80.06**	19.94	240	0.13
Vitamin K (phylloquinone) (mg)	0.005 ± 0.009	0.02 ± 0.11	20	80	14.79	85.21	364	**0.03**

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