INSECT POLLINATION: COMMODITY VALUES, TRADE AND POLICY CONSIDERATIONS USING COFFEE AS AN EXAMPLE

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Abstract—Science has shown the importance of animal pollinators to human food security, economy, and biodiversity conservation. Science continues to identify various factors causing pollinator declines and their implications. However, translation of the understanding of pollinators' roles into current policy and regulation is weak and requires attention, both in developed and developing nations. The national and international trade of commodities generated via insect pollination is large. Trade in those crops could be a means of influencing regulations to promote the local existence of pollinating species, apart from their contributions to biodiversity conservation. This paper, using the example of international coffee production, reviews the value of pollinating species, and relates them to simple economics of commodity production. Recommendations are made that could influence policy and decision-making to promote coffee production, trade, and pollinators' existence. Assumptions and considerations are raised and addressed. Although the role of insect pollinators in promoting fruit set and quality is accepted, implementing pollination conservation in forest habitats may require assured higher prices for coffee, and direct subsidies for forest conservation to prevent conversion to other crop lands. Exporting and importing governments and trade organizations could establish policy that requires insect pollination in the coffee certification process. The European Parliament and the North American Free Trade Agreement could be instrumental in creating policy and regulation that promotes insect pollination services in coffee production. The reciprocity between the services of insect pollinators in certified coffee production and their services in forest biodiversity production should be implicit in future policy negotiations to enhance both systems.

Keywords *animal pollination, trade, commodities, policy, biodiversity, conservation, coffee*

INTRODUCTION

The roles of pollinating species in the generation of human foods and biodiversity production have been well-established (Buchmann & Nabhan 1996; Kevan 1999; Klein et al. 2007; Ollerton et al. 2011). The scientific understanding of the factors underlying declines in pollinating species and negative impacts upon certain pollinators and biodiversity is not so well-established and continues to be researched (Allen-Wardell et al. 1998; Kevan 2001; Biesmeijer et al. 2006; Potts et al. 2010; Brittain & Potts 2011; Mayer et al. 2011). However, the translation of much of what is understood about the importance of pollination into government policy and legislation is weak by comparison. This is often attributed to scientists not wishing to be seen as advocates (Sisk et al. 2011), and the disparate natures of modern science and government policy. Where legislation concerning pollinating insects exists, it is often based on commercial honey bee (*Apis mellifera*) operations managed mainly for honey production, rather than pollination, outside of North America (Tang et al. 2007), and may ignore the diverse array of insects that contribute pollinating services regionally.

There is no specific international treaty that focuses on the conservation of pollinating species and provides the ratified basis of national laws. General policy on pollinator conservation arises from the 1992 United Nations Convention on Biological Diversity. In 1996, the Conservation and Sustainable Use of Agricultural Biodiversity Program was created under the 1992 Biodiversity Convention and used in 1998 to convene the São Paulo Declaration on Pollinators. This declaration led in 2000 to the formation of the International Pollinator Initiative (IPI) (International Pollinator Initiative 1999), and a later (2002) Plan of Action (POA) (Byrne & Fitzpatrick 2009; Williams 2003). The principal aims of the Plan of Action comprise monitoring of pollinators and factors affecting them, upgrading taxonomic information, refining the economic values of pollination services, and promoting the conservation/restoration of pollinator diversity in managed and natural ecosystems. Each aim further involves assessment, adaptive management, capacity building, and mainstreaming. These aims are to be co-ordinated and conducted at a world-wide level (Williams 2003). Although the IPI-POA is only an *agreement* among nations, it is the basis upon which most of the current pollinator conservation and protection research and concern rests. The POA, however, does not mention trade or policy.

The African Pollinator Initiative placed emphasis on mainstreaming pollination science into policy decisions (Eardley et al. 2006). Mayer et al. (2011) identified a series

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of questions that could direct future pollination research and touched on the need for policy involvement. This point was developed further by Biesmeijer et al. (2011), who identified the societal and policy aspects of pollination research as vital in furthering the interest of pollination services. In 2009, the International Risk Governance Council identified the need for policy in sustaining pollination services, and defined the risks related to pollinator declines in addition to the deficits in policy, governance and understanding (IRGC 2009).

In this paper, we review evidence for the huge economic value of pollination services and the value of the crop commodities that are traded internationally. Using the example of international production of coffee and the trade that it generates, we indicate how a greater incorporation of pollination by managed and wild pollinators could enhance yields and adjacent biodiversity maintenance. We indicate how the implementation of this ecological idea has to be reconciled with socio-economic issues of commodity trade at local and international scales in order for policy changes to occur. This paper is an initial foray into the process of integrating insect pollination services into policies directing agricultural coffee production. We make suggestions and recommendations to government and non-government agencies that could facilitate this process.

WHICH POLLINATION SYSTEMS SHOULD BE FOCUSED ON?

Flowering plants exhibit enormous variation in their manner of pollination and fruit/seed set. The reliance of world crop production upon animal pollinators was reviewed by Klein et al. (2007), who identified a wide range of dependency, from essential to non-essential. The success of efforts to involve greater pollination from animal pollinators will depend on the degree to which their service is vital to a given commodity's production (Richards 2001) and subsequent trade. Thus most attention should be placed on those crops for which animal pollination is essential, or may increase the efficiency of, fruit/seed set. This systems approach assumes that a regional decline in the abundance of pollinators and that a pollination "deficit" (Steffan-Dewenter et al. 2005; Aizen et al. 2009; Bauer & Wing 2010; Potts et al. 2010; Cameron et al. 2011) exists in that commodity's production, and that intervention can reduce that deficit. However, there is ongoing debate about this issue (Ghazoul 2005a,b; Steffan-Dewenter et al. 2005).

ASSESSED GLOBAL VALUES OF ANIMAL POLLINATION SERVICES

The assessments provided by the literature are in constant flux because of changing commodity prices on world markets, and especially because of revisions based on a growing awareness of the role of animal pollinators in crop production. The equation – Pollination Service Value = V x D x P (Southwick & Southwick 1992; Drucker 2004) where V is the annual crop value, D is the assumed level of dependence on insect pollination, and P is the proportion of insect pollinators visiting the crop that are honey bees, is not the most accurate model for measuring service value because of the inherent limitations of the assumptions and the overt bias towards honey bees' services (see Allsopp et al. 2008; Bauer & Wing 2010 on this point). Moreover, they do not consider the elasticities of costs with changes in supply and demand (Southwick & Southwick 1992; Kevan & Phillips 2001). This important point is often overlooked by valuations done by ecologists: declines in crop production are often met by consequent increases in demand and prices.

Despite those limitations, Drucker (2004), using the above model, estimated the global annual service value of pollinators to be 65-70 billion US$. Newer (2005) estimates are approximately 225 billion US$, globally (Gallai et al. 2009). These figures reflect the simple value of the produced commodity, and not the total value of the traded commodity. A further salient point is a comparison between the value of crops that are pollinator-dependent and those grown independently of pollination: pollinated crops were valued at 761 €/ton (approx. 1050 $US in 2009), whereas pollinator-independent crops realized only 151 €/ton (approx. 208 $US) (Gallai et al. 2009). This finding is complemented by Ashworth et al. (2009), who reported that in Mexican agriculture pollinator-dependent crops generated both greater crop volume and crop revenue per unit area than pollinator-independent crops.

Southwick & Southwick (1992) and Drucker (2004) concluded that the value of insect pollination services are very large and many times the direct value of honey bee products. Furthermore, the value of commercially-managed insect pollination services is small compared to those provided by nature (Drucker 2004). Allsopp et al. (2008) conducted a study that determined the relative contribution of managed and wild pollinators to deciduous fruit production in South Africa and concluded that the contributions of both wild and managed pollinators had been grossly undervalued. In that study, managed pollinator services contributed 28-122 million US$, for which producers paid only 1.8 million US$. By contrast, wild pollinators' services were worth 49-310 million US$, for which producers paid nothing. This important study demonstrates well the extent to which wild pollinators have been overlooked and the bias towards managed pollinators. New research by Breeze et al. (2011) complements the conclusions of Allsopp et al. (2008), these authors reporting that in the UK, wild pollinators were providing about 66% of the agricultural crop pollination, and managed pollinators, only 34%. Yet the yields of UK crops pollinated by insects rose by approximately 54% since 1984, indicating the capacity of wild pollinators to sustain this increase. The evidence presented in this section indicates that there is a strong economic rationale for enhancing the role of insect pollination in global food production, especially that of unmanaged pollinating species (Kremen et al. 2007; Aizen et al. 2008; Klein et al. 2008; Garibaldi et al. 2011).

SCOPE AND RATIONALE OF THE PRESENT STUDY

The scope of the IPI-POA is necessarily broad and extends across many crops, species and regions. However the production, marketing, and trade of insect-pollinated crops tend to be commodity-specific, despite the ecological commonness of their pollination. We had the option of

examining a broad range of commodities, their pollination and trade policy, or selecting a single commodity that benefits from insect pollination. For reasons of simplicity, coupled with the availability of extensive scientific and economic literature, we selected a single commodity, coffee. Should the scheme proposed for coffee, even with its being several species with different pollination needs for fruit/seed set, be successful, it could be adapted for application to other insect-pollinated crops.

Commercial coffee production is based mainly on two species; *Coffea arabica* and *C. canephora* (Ngo et al. 2011). The species *canephora* is pollinator dependent for fruit set. The species *arabica* is largely wind pollinated, but fruit set increases markedly with insect pollination (Roubik 2002a; Klein et al. 2003a,b). The production of coffee extends from Central and South America to the Caribbean, West Africa, Eastern Africa, and various regions of Asia, where it figures prominently in the economy of these nations. The global value of the coffee trade is large, approximately 80 billion US$/y (International Coffee Organization 2011). International trade in coffee is co-ordinated through the International Coffee Organization, which has strong interests in the manner in which coffee is grown and traded among its member nations (International Coffee Organization 2011). There is a well-developed literature on the economics of coffee production in the Americas and Asia, and a growing literature on the ecology of commercial coffee production (reviewed in Ngo et al. 2011). There is also a growing body of research on the relationships among coffee pollination and biodiversity production in wild adjacent regions (e.g. Ricketts 2004; Klein et al. 2008; Klein 2009; Jha & Dick 2010) and the biodiversity of different types of coffee ecosystems.

ASSUMPTIONS OF APPROACH AND RELATED CONSIDERATIONS

It is assumed that insect pollination is a direct adjunct to production in both *C. arabica* and *C. canephora* by raising both the quantity and the quality of the crop, so enhancing trade. It is also assumed that these benefits may cover the costs of management of all pollinators, including their habitats. A further assumption is that a positive feedback can develop between the insect pollinator-enhanced commodity and its trade. Given that our paper considers coffee production as part of a regional ecosystem, it is further assumed that valuable externalities exist between pollination of coffee by insects and adjacent biodiversity maintenance. These assumptions are addressed later in the paper.

Other considerations for developing revised policy and certification involve the economics of pollination services and coffee production, and include, in no apparent order:

1. determining the value of contributions of both managed and wild pollinating species to coffee production in a given region in the manner of Allsopp et al. (2008) for deciduous fruit crops in South Africa. Related to this consideration is knowing what is(are) the cost(s) of replacing insect pollinators for different coffee crops. Should wild pollinating species be important pollinators of the crop, it is necessary to know the costs of maintaining their habitat and its forgone economic opportunity.

2. from a biodiversity conservation perspective, it is important to know what is(are) the contribution(s) of the pollinating species to adjacent productivity of wild plant species and the food webs they comprise.

3. given that a greater involvement of insect pollinators has an economic cost, it is important to know if subsidies (incentives, or credits) are available to producers for having wild lands next to coffee plantations to offset costs.

4. implementation must consider the type of plantation ownership (i.e. private or corporate), the level of technology used (i.e. organic operation or synthetic inputs), the size of plantation, and distance to native forest lands.

Consideration of the socio-economics of the coffee trade is critical in any proposed venture. Kitti et al. (2006) indicated that

"... policy measures such as trade-related standards, premiums, tax reliefs, or government institutions are necessary for adoption of biodiversity-friendly growing practices".

Similarly, Allsopp et al. (2008) commented that

"...monetary valuation dominates natural resource conservation management decisions and policy-making".

Those quotations are important because they address the heart of the issue, that ecosystem-based objectives require the vehicles of economics and policy to be realized successfully, especially in the face of unstable prices and other risk factors (Benítez et al. 2006). Thus it is necessary to relate any proposed venture to consumer demand and market prices for the product and whether or not any trade standards are in effect, either by the coffee industry or in regulations of importing nations. It is also important to consider whether or not a particular nation factors in the costs of insect-pollinated sustainable coffee production into a broader biodiversity conservation program. Perhaps the most important economic criterion determining the acceptance of greater insect-pollinated coffee production is if it is consistently profitable for the independent farmer. Thus, as Kitti et al. (2006) and Allsopp et al. (2008) indicate, an agro-ecological venture soon becomes an economic venture.

EVALUATION OF THE ASSUMPTIONS AND CONSIDERATIONS

Assessing the efficacy of insect pollination of coffee species

Wilmer & Stone (1989) were among the first to report the pollination of *C. canephora* by solitary bees in Papa New Guinea and its role in fruit set, leading them to outline measures to increase this type of pollination in plantations. Klein et al. (2003a) reported a great increase in the fruit set of Indonesian *C. canephora* when flowers were exposed to open pollination from insects and/or wind and pollen from different plants, the increase being approximately from 15% to 70%. In a different study, Klein et al. (2003c) reported

that fruit set increased directly with the number of bee species visiting the flowers, and with the number of individual bees across all species. All those authors reported that the degree of fruit set declined the further away *C. canephora* coffee trees were from adjacent wild forest. In keeping with this result, the number of social bee species visiting coffee flowers also declined with increasing distance from adjacent forest. These results and those of Klein et al. (2008) attest to the role of wild bees in effecting pollination for *C. canephora*, especially those for which forest is the natural habitat.

The flowers of *C. arabica* are largely self-pollinating, but fruit set benefits from insect cross-pollination. Klein et al. (2003a) reported an increase (12.3%) in fruit set in this coffee species when insect visitation was allowed, a smaller increase than that seen in *C. canephora*. The percentage fruit set in *C. arabica* increased directly with the number (or diversity) of bee species, but not with the number of individual bees. The number of social bee species visiting the *C. arabica* flowers declined significantly with increasing distance from neighbouring forest (Klein et al. 2003b). The results of these studies indicate that highly successful fruit set rests on a rich wild bee community dependent on wild forest habitat situated less than a half kilometer from coffee plantations.

Ricketts et al. (2004) conducted similar pollination-productivity experiments on *C. arabica* in Costa Rica. That study reported a 20% increase in coffee fruit yield based on pollination by wild bees living with in 1km of forested land. A further benefit of bee pollination was that the overall quality of the fruit was increased by reducing the prevalence of distorted fruit by 27%. Distorted fruits must be removed from the harvested crop, adding extra expense to the producer. Ricketts (2004) also found that bee visitation rates and amounts of pollen transferred were higher when coffee plants were located less that 100m from forest fragments, and concluded that forest fragments, by providing habitat for a great diversity of wild pollinators, enhanced the reliability of coffee flower pollination by reducing dependency on managed honey bees. Vergara & Badano (2009) measured fruit production in Mexican coffee plantations that had low and high-impact management systems. They reported that the pollinating insect species richness and diversity of the low-impact plantations was greater than that of the high-impact lands. Fruit yield was also positively related to the diversity and species richness of the pollinators, indicating that the pollination service value was amenable to direct human management.

Roubik (2002a) presented evidence of global increase in coffee (*C. arabica*) yields and attributed them to the presence of introduced Africanised honey bees. He reported that bee pollination generated heavier fruits. Where national declines in yields were noted, Roubik (2002a) attributed the decline to a lack of pollination service linked to intensive agricultural land management practices that eliminated pollinator habitats. Roubik (2002b) reported that in Panama, Africanised honey bees were the principal pollinators of different cultivars of *C. arabica,* and that coffee flowers near forests attracted more bees, both native and Africanised, than flowers distant from forest vegetation.

The flower visitation rates and efficiency of pollination of coffee flowers may vary among insect pollinating species and regions. This issue has been reviewed by Free (1993) and more recently by Ngo et al. (2011). In Central and South American countries (Brazil, Costa Rica, Ecuador, Jamaica, Mexico, Panama) the honey bee is seen to be the most important pollinator species for *C. arabica*. This is consistent with the origins of both honey bees and *C. arabica* in Africa. Amaral (1972, cited in Free 1993) reported that the larger-bodied bees (*A. mellifera* and *Melipona quadrifasciata*) were more efficient pollinators of *C. arabica* flowers than smaller bee species. For *C. canephora* grown in Papua New Guinea, a leafcutter bee *Creightonella frontalis* was reported as the main pollinator (Willmer & Stone 1989). Klein et al. (2008) reported on the importance of a range of pollinating insects visiting *C. canephora,* their relationships to each other, coffee flowers, and their local environment. These same authors indicated that pollination success may reflect more the diversity of pollinators' niches and their interactions in the coffee-pollinator community than upon species richness. A similar increase in crop yield with functional diversity of pollinators has been found for *Cucurbita moschata* (Pinkus-Rendon et al. 2005; Hoehn et al. 2008) and strawberries (*Fragaria* sp.) (Chagnon et al. 1993). However, in highly-impacted areas of Ecuador with few forest remnants, Veddeler et al. (2008) reported that coffee crop yield increased directly with the density of wild social bees visiting coffee shrubs, and not the number of flowers per plant.

A consistent picture emerges from all those independent studies conducted on several continents. The pollination ecology of coffee is very generalized (Klein et al. 2008) and pollination by diverse insect pollinators of both *C. arabica* and *C. canephora* can offset potential pollinator deficits and increase fruit yield and quality. The role of nearby forest fragments that support a diversity of wild pollinating insects is a direct adjunct to production of both coffee species, and should be a component of modern policy to manage coffee on a sustainable basis.

Scale of operations and feasibility

In Mexico the majority of coffee plantations are small, less than 5 ha (Moguel & Toledo 1999), often in association with forest fragments that provide a canopy of shade. By contrast, sun coffee monocultures are much larger, and are grown in the absence of shade-conferring native trees and shrubs. Given the results of Klein et al. (2003a,b,c) and Ricketts (2004) that insect-pollination is most effective when coffee plants are less 500m from forest, and the study of Vergara & Badano (2009) on rustic plantations, it would appear that most plantations (at least in Mexico and Costa Rica) are conducive to active management for insect pollinators, especially wild species. Larger areas of sun coffee monocultures might require use of managed hive bees interspersed through plantations to enhance pollination. Small plantations adjacent to forests would be inclined to use fewer synthetic inputs than large sun coffee

monocultures, a feature that would favour greater involvement of pollinating insects in production.

Assessing benefits of insect pollination of coffee to adjacent biodiversity

Although the benefits of wild pollinators to coffee pollination have been established, the contribution of coffee pollinators to adjacent biodiversity has been little-researched by comparison. *Coffea arabica* has a short period of synchronous blooming each year, but *C. canephora* may bloom synchronously but over several months (Klein et al. 2008), thus coffee plantations do not provide a continuous source of nectar to bees. However, shade coffee plantations in southern Mexico contained native bee communities that transported the pollen of native forest trees far across the landscape, linking forest fragments with shade coffee groves, and making a vital contribution to gene flow among native forest trees (Jha & Dick 2010). Karanja et al. (2010) studied insect pollinator visitation in organic and conventional coffee plantations and surrounding unmanaged areas of Kenya. Pollinating insects on coffee flowers also visited flowers of 42 other wild plant species that provided alternative floral resources. That study also found highly significant ($P < 0.0001$) statistical relationships between the richness of plants and pollinating bees in both the organic and the conventionally-managed plantations. Karanja et al. (2010) raised a further important management issue. Maintenance of insect populations that pollinate coffee flowers is vital when coffee plants are not in bloom, and this role is provided by other diverse flowering plant species adjacent to coffee plantations. Thus there is a pollination reciprocity that is valuable to biodiversity production and agricultural production that should form part of any policy considerations, and be the basis of future research in coffee growing regions. The greatest biodiversity is reported to reside in rustic and shade-coffee-certified plantations (Mas & Dietsch 2004; Philpott et al. 2007): large sun coffee monocultures likely contain least native biodiversity. Thus the opportunity for significant ecological reciprocity is possible only in the rustic and shade coffee systems in proximity to native forest areas.

What constitutes optimal adjacent forest cover for coffee and its pollinating species?

There are four types of Mexican coffee plantation systems that comprise trees (Moguel & Toledo 1999; Hernández-Martínez et al. 2009). These are shaded monoculture, commercial polyculture, traditional polyculture, and rustic, the amount and size of native trees increasing with progression to the rustic category. Shade coffee has been associated mainly with the traditional polyculture in this classification scheme, and is grown mainly by small-scale community producers. Moguel & Toledo (1999) identified this forest category as important habitat for both native plants (trees and epiphytes) and animals (all Chordates and Arthropods). The degree of shade cover is an important determinant of coffee yield: there is a positive relationship between 23-38% shade, but production may decline when cover exceeds 50% (Soto-Pinto et al. 2000). This relates to the studies of Klein et al. (2003b, c) who showed that for both *C. arabica* and *C. canephora*, the numbers of solitary bee species increased with light intensity of the plantation (i.e. habitat openness), and correlated with this, an increase in fruit set with increasing light intensity for *C. canephora* (Klein et al. 2003c).

Recent studies have investigated the biodiversity attributes of different Mexican shade coffee plantations. Gordon et al. (2007) analyzed the avian and mammalian richness of coffee plantations, and López-Gómez et al. (2008) measured the tree species richness and vegetation physical structure on coffee farms. However, neither of these studies reports on the composition of the pollinator communities of these areas. Similarly, the pollinator community structure of coffee plantations other than traditional shade systems has yet to be measured. This is an important next step, especially if shade coffee plantations are to be identified as an important agroecosystem for sustainable certified coffee production involving greater insect pollination. Important research from Jha & Vandermeer (2010) indicates how the bee species richness and abundance can be correlated with the tree vegetation cover in Mexican shade coffee plantations. Their research findings applied to solitary bees, cavity and wood-nesting bees and ground nesting bees. Most importantly, these authors found that the composition of the pollinating bee community was related directly to local farm land management practices (Jha & Vandermeer 2010). Specifically, these practices provide niches for diverse species of the pollinating community and also provide a continuity of nectar resources across seasons. Veddeler et al. (2008) concluded that the deliberate retention of old trees as bee nesting sites, and the presence of flowering plants that provide nectar year-round might promote a high abundance of bees to pollinate coffee flowers, but Priess et al. (2007) remarked that these features of land management have still to develop at a wider scale. The species composition and structure of shade coffee habitats can vary, and the distinction between rustic forest and traditional shade polyculture may be blurred. Mas and Dietsch (2004) called for a greater rigour in the definition of what is termed shade coffee landscape as it pertains to biodiversity conservation and trade certification of the coffee produced within it. This definition ought also to include an assessment of the animal pollinator community (Ngo et al. 2011).

Economic assessment of pollination services in coffee plantation mosaic habitats

Ricketts et al. (2004) calculated the economic value of insect pollination services provided by Costa Rican forest patches to coffee production. They reported that the value of the pollination service was comparable to potential alternative land uses, but far exceeded conservation incentives available to farmers. These authors' calculations did not include the value of other forest environmental services (e.g. water retention or carbon sinks), and concluded that the forest habitat portion of the coffee landscape yielded a "win-win" situation for both forest biodiversity and coffee culture. Gordon et al. (2007) could not correlate profitability with biodiversity measures in Mexican coffee plantations, but

reported that the most diverse plantations were among the most profitable, regardless of prevailing coffee prices.

Olschewski et al. (2006) were critical of the economic assessment of Ricketts et al. (2004), arguing that valuations based on market prices and fruit yields, alone, were inadequate. They reported from their Ecuadorian and Indonesian studies that the absolute value of pollination services was similar in the two regions, and that the pollination service value was influenced directly by the amount of intact forest within 400 m of the coffee trees. In both Sulawesi and Ecuador, coffee revenues decreased markedly with increasing distance to intact forest. However, these authors reported that the value of alternative land uses was greater per unit area than the pollination service value of the forest. Priess et al. (2007) calculated the pollination service value of forested land in Sulawesi to be 46€/ha (approx. 52 US$), based on 2001 prices and data. That does not create a strong incentive to invest more in insect pollinator forest habitat, especially during times of depressed coffee prices, unless the other service values of such lands (especially the increased stability of crop pollinating bee communities (Klein 2009), nutrient capture, soil and water rentention, carbon sinks, and contributions to regional and/or continental biodiversity) are considered as additional adjuncts to production. There are, moreover, additional local human uses of tropical forest (e.g. fuel, construction wood, plant fibre, foods, medicines) that generate considerable value beyond the environmental services. Priess et al. (2007), on the basis of simulated land use changes in Sulawesi, indicated that preservation of patches of natural forest in the coffee agriculture mosaic could benefit both local economy and ecology, noting that reduced yields of coffee from reduced pollination of the flowers leads to greater conversion of forested land to alternate crop production. Olschewski et al. (2006) concluded that a higher realized price paid by a public desiring the continuation of coffee production in shade-grown systems would create the incentive to maintain this practice. Kitti et al. (2006) conducted an economic analysis of shade and sun coffee production in Costa Rica in which prices and protection fee (forest subsidy) were factored. They also found that higher prices for shade coffee and very high forest subsidy fees (as high as 358 US $/ha in an optimal scenario) would be necessary for shade coffee production to thrive versus sun-grown coffee. From an ecological perspective, shade-grown coffee is preferable to sun-grown monocultures because most natural biodiversity occurs on shade-protected plantations (see Philpott et al. 2007 and 2008 for Chiapas, Mexico, and Sulawesi, respectively). However, as Kitti et al. (2006) indicate, applying ecological considerations must be reconciled with economic realites.

Other economic analyses of shade coffee production yield similar conclusions. Perfecto et al. (2005) contended that high consumer prices for shade coffee that has low market penetration (10.5% of all Latin American exports) might hurt consumption, and so regional production. These authors argued that subsidies for shade coffee, apart from higher consumer prices, would be needed to sustain shade coffee production. Moreover, based on their analyses, high price premiums for shade coffee should go directly to growers to facilitate forest conservation. Benítez et al. (2006) envisaged subsidies from certification programs as the only way to maintain environmentally-friendly coffee production in the face of sun monoculture and other forms of land use. This is especially in view of the lower per unit area production of the shade coffee system compared to the sun coffee monoculture (Perfecto et al. 2005).

The conclusions generated from global surveys of crop production also have direct implications for coffee production and policy makers. A transition to intensely managed crop land may have serious negative consequences for long-term crop production, and especially for pollinator-dependent crops (Aizen & Harder 2009). Relationships between the growth in yield and the stability of crop production of pollinator-dependent crops have been analyzed in detail for intensely-cultivated agricultural regions (Aizen et al. 2008; Garibaldi et al. 2011). Aizen et al. (2008) presented evidence for an impact of pollinator shortage on crop yield at the global scale. Garibaldi et al. (2011) endorsed the management of pollinators and their habitats for their service to fruit set because of their positive effect on the yield and production stability of pollinator-dependent crops. Those latter authors endorsed further managed use of pollinators for certain crops, suggesting that such a practice could improve yields and reduce the need for more land cultivation.

Ricketts et al. (2004) indicated that the significance of the "shade" in shade coffee systems was really the proximity to forests that provide habitat for wild pollinators. Thus discussion of the role of these forest "mosaics" or "landscapes" is as much about the pollinators' habitats as it is about other aspects of native plant and animal biodiversity, especially given the observed reciprocity between shade coffee production and pollen dispersal in forests. Linking the diverse values and ecological service roles of forests to coffee production should permeate thinking about certification processes, subsidies and other forms of incentive payments: it is about the entire regional ecosystem, and not just coffee or native forest production. The functional connections between agriculture and ecology were detailed in Kevan et al. (1997), in which the term "natural mutualism" was used to define the natural services that supported agriculture. Insect pollination of crops (including coffee species) is such a natural mutualism whose importance forms the basis of the conclusions of Garibaldi et al. (2011).

Certification and insect pollination of coffee

There are three main types of certified coffee (fair trade, organic, and shade coffee), and the criteria for each have been outlined in Philpott et al. (2007). The three certifications do not use insect pollination as an explicit criterion. However, it may be implied in organic and shade-grown varieties. From a policy perspective, it is important that consideration of pollination by managed and wild pollinating insects be an explicit part of the certification process, and that consumers be aware of how that type of coffee has been generated. This could be applied not only to coffee grown in rustic and traditional shade systems, but also to the sun monoculture, shaded monoculture and commercial polyculture production systems identified by

Moguel & Toledo (1999). In these more intensive systems, pollination involving more Africanized honey bees (Roubik 2002b), as opposed to wild bees is a possible management option.

The explicit mention of insect-mediated pollination in coffee production in certification is not likely to detract from the public's attitude to that type of coffee: it could enhance it, given the generally favourable esteem in which pollinators are held. Francis & Francis (2006) indicated that the public demand for higher quality coffee was growing. This would favour environmentally-friendly coffee production over that from sun monocultures. A strong public demand for a certified product, coupled with awareness of what it entailed, could be an important factor in driving policy to protect wild pollination services, especially as it would affect prices and, possibly, regional-national conservation incentives. This is the positive feedback between trade and local forest shade coffee production to which we alluded earlier in the paper. Certification may have positive socio-economic benefits to coffee growers, especially when low market prices prevail (Pefecto et al. 2005). Philpott & Dietsch (2003) identified social justice as a concept to be linked with certification, quite apart form conservation issues, and advocated combining the three certifications into a single, rigorous certification, together with participation of farmers to enhance the conservation and socio-economic aspects of coffee growing. The inclusion of pollination by unmanaged and managed insect communities in the certification process is consistent with these objectives.

Roles of governments and non-governmental organizations in promoting pollination services via policy

Concerns about sustainable coffee yields, producers, trade in coffee, and regional social welfare rest on the initial formation of coffee fruits via pollination, which is why a consideration of pollinators must pervade policy and decision-making. Coffee production's enormous annual traded value, combined with its contribution to national economies and human livelihoods, has the power to influence production policy through multi-lateral government organizations, individual governments and coffee trade organizations. Treweek et al. (2006) identified the major challenge for policy makers as the recognition of biodiversity as the basis of sustainable agriculture, and to ensure that all agriculture and its trade is conducted respectful of biodiversity conservation. To achieve this, Treweek et al. (2006) emphasized identifying opportunities to incorporate biodiversity into policy making. We contend that insect pollination services to coffee production and other food crops represent such an opportunity that could be taken by agencies representing sustainable agriculture, coffee production and trade, plant-pollination relations, biodiversity conservation, and community development. Work on how to implement this concept has already been initiated by Kremen et al. (2007) who developed a model showing how insect pollination systems may be influenced by market forces and their interactions with policies determining agricultural land management. This conceptual model could be integrated readily with the predictive models of Jha & Vandermeer (2010) to implement pollinator habitat management at the plantation level. We contend that these authors' approaches should be applied to different coffee producing regions when revising policy.

The International Coffee Organization already conducts much research into aspects of coffee production that benefits the industry, such as improving the genetics of coffee varieties for increased yield and disease resistance (International Coffee Organization 2011). This organization, apprised of the role of insect pollinators, could develop policy to promote insect pollination services in all coffee production. This could be combined with extension work on how to implement best management practices for pollinator conservation in different coffee growing systems. These need to be developed for coffee grown in South and Central America, Africa and Asia because of different growing landscapes and prevailing management in these regions (Philpott et al. 2008).

There is a large coincidence between the global regions of greatest natural biodiversity and those of coffee production. The coffee growing system has to be linked, conceptually, with its broader natural ecosystem, and the criteria for sustainable coffee production should be incorporated into broader conservation schemes in the same regions (Mas & Dietsch 2004). This is important because floral resources from wild plants are needed to sustain the wild pollinator community that provides coffee pollination services during periods of non-flowering by coffee. Given that financial support will be required to realize and maintain this goal, policy to achieve this could be developed in partnership with farmers and governments of producing nations, and especially those global agencies whose principal aim is preserving native biodiversity. This approach is best combined with a revised rigorous certification scheme that reflects support for both ecosystem and socio-economic benefits, as envisioned by Mas & Dietsch (2004) and Philpott et al. (2007). Complementary policy could be developed by importing nations, given that much of the tropical coffee production is exported. How this revision of certification criteria might affect coffee production in different countries is not known and is beyond the scope of this paper. However, "raising the bar" for certification would create competition among producing nations for the higher-end segment of the coffee market, and especially for *C. arabica* that supplies most of the coffee for the gourmet niche market. This would be beneficial in generating more revenue for those producers of that variety of coffee, and benefits to the environment might follow. Ultimately, it is the quality of the retailed coffee that determines consumer preference and willingness to pay, and not so much the ecological conditions that prevailed on plantations. It is assumed that the quality of post-harvest processing of coffee right up to the retail level would be commensurate with the care given to the cultivation of coffee in certified plantations.

The following examples indicate how governments of coffee–importing nations have already implemented policy and regulations dealing with the manner in which imported food items and natural resources are produced. The

European Parliament placed a legal ban on the import of wild seal pelts and other seal products from Canada in 2011 because of the perceived way the animal pelts were procured (European Commission 2011a). This applies to all member nations of the Union, although individual nations (e.g. The Netherlands) had applied their own, national, ban in earlier years. The European Parliament has also developed a regulatory framework applied to imports of crops that are grown from genetically-modified seeds, fearing what might be the consequences of such genes entering human foods and agriculture (European Commission 2011b). In these two cases, the concern is about the manner in which the products are procured for import. The same consideration can be applied for imported coffee, in which certification reflects particular aspects of production and sale (e.g. under shade, without synthetic chemical input or fairly-traded). Producing coffee under field conditions that promote pollination by unmanaged and managed insect communities is also procurement, and, as such, is open to consideration by the European Parliament and any of its member nations.

A large amount of the coffee produced in Mexico is marketed in Canada and the USA. The North American Free Trade Agreement (NAFTA) among Mexico, Canada, and the USA contains an agreement (under the Commission on Environmental Cooperation) on environmental co-operation to ensure that goods traded among the Parties conform to environmentally-acceptable trade standards. It is within the mandate of the Commission on Environmental Cooperation to develop regulation on the pollination requirements of traded coffee under the terms of the NAFTA. Thus any imported coffee from Mexico could be regulated consistent with plantations having management plans that ensure that appropriate habitat is present to maintain populations of unmanaged and managed pollinators. Again, deliberate incorporation of pollinator provisions into a revised, rigorous, certification process is the effective way to do this.

Both Europe and North America are realizing the consequences of potential pollinator deficits to their own food security (National Research Council of the National Academies 2006; Biesmeijer et al. 2011). On November 16, 2011, European Union lawmakers passed with a huge majority a resolution to protect European bees because of the problems pollinators and food security face at the regional level (World Environment News 2011). Thus, it is plausible that the European Parliament might support policy development to protect coffee pollinators at the international level. Such action is warranted and is completely consistent with the Precautionary Principle. It would also represent an example of a laudable policy initiative by importing nations assisting, simultaneously, the sustainable production of a commodity in producing nations and the biodiversity of their natural environment. While the above discussion relates to Europe and North America, coffee is produced and imported over a greater range of other countries that are free to devise their own policies on how imported coffee is generated. However, any progressive policy developments made by the European Parliament and the NAFTA could emerge for consideration at a regional level (as among the major producers of South and Central America), and at the global level by the World Trade Organization.

CONCLUSIONS AND CONSIDERATIONS FOR POLICY MAKERS

1. Managed and unmanaged insect pollinators, by their abundance and diversity, enhance fruit production and quality in commercial coffee production. This role could offset potential pollinator deficits, directly promote production and trade, and has relevance to all countries in which *C. arabica* and/or *C. canephora* is/are produced.

2. The insect pollination service provided for coffee can extend into adjacent forest regions and promote natural biodiversity maintenance, especially in rustic and shade grown coffee.

3. Maintenance of a community of pollinators that service coffee flowers requires that alternate floral resources are available when coffee shrubs are not blooming. This requires management of adjacent forest mosaic lands to provide pollinator nesting sites and a blooming continuum of other flowering species. This management objective is more readily attainable in rustic and shade coffee plantations than in large sun coffee monocultures.

4. Insect pollination services should be a mandatory component of all coffee certification processes. A single, rigorous, certification that combines the criteria for existing coffee certifications would enhance the ecological and socio-economic aspects of coffee growing.

5. The costs of conserving forest areas adjacent to plantations may need to be offset by higher prices for certified coffee varieties and coupled with incentives and subsidies for biodiversity conservation.

6. The value of the international trade in coffee and the revenues generated for nations and communities enable trade to influence policy and regulation at many levels, from plantations to importing nations. The insect pollination service to coffee is a critical "entry point" into the agricultural and environmental policy process and should be explored.

7. Consumers who seek higher quality coffee and who realize the role of pollinator services can assist the policy process through choice of purchase.

8. Policy development can be undertaken by coffee producing and importing nations and agencies representing the coffee trade. Importing nations could require certified standards of coffee production that favour forest conservation, its contained insect pollinator community, and other biodiversity. This is an opportunity for the NAFTA, the European Parliament, the World Trade Organization, and other agencies engaged in supporting large-scale biodiversity conservation.

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