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Review

Neglected pollinators: Can enhanced pollination services improve cocoa yields? A review

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ABSTRACT

The negative effects of climate change on cocoa production are often enhanced through agricultural intensification, while research institutions and enterprises try to minimize yield gaps with production strategies mitigating climate risk. Ecological intensification is such a production strategy, whereby yield increase is promoted through reduced agrochemical inputs and increased regulating ecosystem services such as pollination. However, we still know little about cocoa pollination ecology and services, although they appear to be key to understand yield functions. Here, we provide an extensive literature review on cocoa pollination focusing on three main aspects: non-plant (external) and plant regulated (internal) factors affecting pollination, pollinator agents, and ecological intensification management for enhancing pollination success and yield. Pollination services by many arthropod groups such as ants, bees, and parasitic wasps, and not only ceratopogonids, may be a way to increase cocoa productivity and secure smallholders income, but their role is unknown. Several environmental and socioeconomic factors can blur potential pollination benefits. Current knowledge gaps preclude our understanding of how to (i) identify the major pollinator species, (ii) disentangle the direct or indirect role of ants in pollination, (iii) design effective habitat improvements for pollination (by litter and shade management), and (iv) quantify the yield gaps due to pollination limitation. Optimizing cocoa pollination alone appears to be a powerful ecological tool to increase the yield of smallholders, but experimental research is required to validate these results in a realistic setting. In general, industry, governments and smallholders need to develop more joined efforts to ecological production strategies. In particular, farm-base management innovations based on robust scientific evidence must be designed to meet the increasing demand for chocolate and to mitigate cocoa yield gaps. This review suggests that diversified systems and associated ecosystem services, such as pollination, can help to achieve such goals.

1. Introduction

Climate change is predicted to have severe impacts on the environment and the crop production (Challinor et al., 2014) through prolonged droughts, pest and disease outbreaks and variations in climate extremes (Rosenzweig et al., 2001; Lobell et al., 2011). In the past 30 years, yields of wheat and maize, two of the most important staple crops, declined considerably due to irregular weather events (Lobell et al., 2011). Similarly to wheat and maize, cocoa (*Theobroma cacao* L.) as the third largest legal crop commodity worldwide (Donald, 2004) has seen significant climate-related yield deficits over the past three years (ICCO, 2016a). In the major producer countries Ghana and Ivory Coast, climate change threatens the current suitability of land used for cocoa, and will likely force farmers to adopt strategies enhancing agro-ecosystem resilience through management improvements (Clay, 2013; Franzen and Borgerhoff Mulder, 2007; Clough et al., 2009; L & derach et al., 2013; Schroth et al., 2016). International enterprises and research institutions are aware of these constraints (ICCO, 2015; MARS, 2017), but current cocoa production strategies lack effective ways of securing long-term yield and climate adaptation. For example, farmers are advised to intensify their production through replacement of old and heterogeneous plant material with genetically engineered varieties, and trained to efficiently apply pesticides and fertilizer to reduce yield gaps (WCF, 2016a; MARS, 2017). This approach increases short-term yields and farmer benefits but it can have long term disadvantages such as biodiversity loss, disruption of essential ecosystem services and the dependence of farmers on external inputs (Tscharntke et al., 2011). Sustainable cocoa production strategies need to buffer current yield deficits while assuring long term ecological and economic benefits for all cocoa stakeholders.

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Compared to conventional agriculture, highly diversified systems and their provision of ecosystem services through ecological intensification may be key for long-term solutions (Ponisio et al., 2015). Ecological intensification balances external inputs and advocates for the enhancement of ecosystems services through farm-based adaptations to reduce yield gaps and improve farmer livelihoods (Bommarco et al., 2013). For example, yield gaps in small-scale agricultural systems can be reduced by enhancing pollination services (Garibaldi et al., 2016). Simple management improvements such as the addition of shade trees can have positive effects on both pollination and yield while also likely reducing climate risks (Wanger et al., 2014). Indeed, pollination success rather than nutrient limitation determines cocoa fruit set and yield in Indonesia (Groeneveld et al., 2010). However, major knowledge gaps include pollination ecology, pollinator agents, and their potential for ecological intensification. Addressing these pressing research issues will help to overcome the climate-related yield crises in cocoa production (Deheuvels et al., 2014a, 2014b; COCOAPOP, 2016).

Here, we review the limited knowledge on cocoa pollination to discuss the ecological and economic potential of pollination services to buffer current yield deficits. We present three important topics that address the main aspects and constraints on cocoa pollination ecology: i) external and internal factors affecting pollination success from flowering to harvesting, ii) the role of pollinator agents on pollination intensification, and iii) current ecological intensification methods for increasing yields. In the final section we discuss where future research efforts are needed.

2. Literature review

We reviewed published literature from 1939 to 2016 in the Web of Science and Google Scholar using the search string “TS = ((cocoa OR cacao) AND (pollinat*))”, with additional searches of relevant studies on cocoa and climate change, hand pollination, arthropod diversity and ceratopogonids ecology. We found 108 books, articles, PhD dissertations and manuals, of which 67 were available for revision (Appendix A). We also extracted information from the title and abstracts of unavailable literature where possible and merged it together with the available literature in a common database. Overall, there were two main peaks in the number of publications: 1971 > 1985 and 2001 > 2016 with 36 and 37 published materials, respectively. The majority of study sites of the published material were in Ghana (23), Costa Rica (11) and Brazil (8). We found only two published reviews and two book chapters specifically focusing on pollination and pollinator ecology (Glendinning, 1972; Winder, 1978; Entwistle, 1972; Wood and Lass, 2008) published in the 1970s and 1980s with studies dating back to 1910. In recent years three review papers on agroforestry systems highlighted the importance of pollination ecology for cocoa yields (Donald, 2004; Klein et al., 2008; Tscharntke et al., 2011; Wielgoss et al., 2014).

3. The cocoa cycle from flower to harvest

The cocoa pollination cycle from flowering to pollination, fruit set, fruit development and pod harvest is regulated by external and internal mechanisms, which can be divided into four phases: flowering, flower opening and pollination, flower fecundation and fruit set, and harvesting (Fig. 1) (Table 1).

3.1. Flowering (Phase I)

The cocoa tree (*Theobroma cacao)* produces up to 125,000 miniature white and pink-purple nectar-guide flowers of 10 > 15 mm diameter in clusters of 14 > 48 flowers cushions, also referred as cauliflowers, along its main branches (Glendinning, 1972; Wood and Lass, 2008; Falque et al., 1995; Somarriba Chavez et al., 2010). Cushions are formed in old leaf-axis of young healthy wood, with flower buds requiring in general 30 days to emerge and mature (Wood and Lass, 2008). The floral structure comprises five sepals, five petals, 10 stamens (male structure), one ovary (female structure) of five chambers containing the ovules, and five unfertile elongated staminodes (Glendinning, 1972; Wood and Lass, 2008).

3.1.1. Flower mechanisms to enhance pollinator visitation

Flower color, structure and volatiles are highly important for inducing pollinator visitation. For example, staminodes are highly attractive to pollinators due to their color and odor molecules produced (Young et al., 1984; Young and Severson, 1994). Young and Severson (1994) studied the effect of steam distilled oil properties and attractiveness to pollinators in nine genetically contrasting cocoa cultivars in Costa Rica. They classified the cultivars in three different clusters, of which one ancestral-type of cocoa formed one cluster alone with the highest molecular weight compound and attractiveness. These results indicate that cultivars from artificial selection methods can be less attractive to pollinators than wild-types of cocoa cultivars, highlighting the potential of native cocoa varieties for enhancing pollinators and pollination success.

3.1.2. Driving factors for flower production

Precipitation is known as the main driver initiating cocoa flowering (Glendinning, 1972; Wood and Lass, 2008). Glendinning (1972) observed that flower frequency in plantations in Ghana was low during the dry season (January > March), but increased throughout the rainy season (April). Similar flowering patterns are described in the Americas, West Africa and South East Asia (Young, 1983; Omolaja et al., 2009; Chumacero de Schawe et al., 2013; Bos et al., 2007a). Beside precipitation, factors such as cultivar genetics and management practices can affect flower production. In Ghana, for example, flowering pauses in Lower-Amelonado between June and November, while Upper-Amelonado produces flowers throughout the year (Falque et al., 1995). Glendinning (1972) observed that flower abundance increased during harvesting, suggesting that pod removal can also trigger flowering, as the tree allocates energy in flower production rather than fruit development (Entwistle, 1972; Valle et al., 1990; Bos et al., 2007a).

3.2. Flower opening and pollination (Phase II)

Flower opening, or anthesis, starts in the afternoon when a fully mature flower bud splits open, and it continues opening during the night. Early in the morning the anthers release the pollen grains when the flower is fully open, and later in the afternoon the style matures. This is the stage when the flower is more receptive for pollination (Wood and Lass 2008; Chumacero de Schawe et al., 2013). The average flower lifespan is two days after opening, and unpollinated flowers abscise after 36 h (Glendinning, 1972; Entwistle, 1972; Groeneveld et al., 2010).

Cacao pollination is the process of pollen transportation and deposition on the flower style performed by a pollinator agent (Falque et al., 1995; Wood and Lass, 2008). Pollination success occurs when a minimum of 35 > 40 pollen grains (Entwistle, 1972; Kaufmann, 1975), are deposited on the style (Falque et al., 1995). The general consensus is that small ceratopogonids (Diptera) are the main cocoa pollinator agents (Entwistle, 1972; Winder, 1978; Young, 1982, 1986; Tscharntke et al., 2011). Some authors have reported other insects as casual flower visitors, but the majority failed in recording fruit set to corroborate their pollination efficacy (Winder, 1978b; Adjaloo and Oduro, 2013; Deheuvels et al., 2014a,b; de Schawe et al., 2016). Pollination via non-animal agents, such as wind, is unlikely due to the plant self-incompatibility in most cocoa trees and the flower structure (Posnette 1940; Chapman, 1964; Leston 1970), but successful wind pollination has been reported in Costa Rica (Glendinning, 1972). Wind can play a major role by transporting the pollinators along larger distances, as directed ceratopogonids flights can only cover a few meters (Bos et al.,