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Complementarity and synergisms among ecosystem services supporting crop yield

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ABSTRACT

Understanding how ecosystem services interact to support crop yield is essential for achieving food security. Here we evaluate the interactions among biotic pest regulation, pollination, and nutrient cycling. We found only 16 studies providing 20 analyses of two-way interactions. These studies show that multiple services limit crop yield simultaneously. Complementary effects (no interactions) between ecosystem services were the most common, followed by synergistic effects (positive interactions), while evidence for negative interactions was weak. Most studies evaluated two levels of service delivery, thus did not quantify the functional response of crop yield. Although this function is expected to be non-linear, most studies assume linear relations. We conclude that the lack of evidence for negative interactions has important implications for agricultural management.

1. Introduction

Biodiversity improves human wellbeing through various ecosystem services, including material (e.g. food, fibers, timber), regulating (e.g. pest regulation, pollination, and nutrient cycling), and non-material (e.g. health, aesthetic, spiritual, education, or recreation) contributions (Pascual et al., 2017). However, approximately 60% of the ecosystem services evaluated during the last decade are being degraded (Millennium Ecosystem Assessment, 2005). This alarming trend is particularly important for food security and agricultural sustainability, as crop yield ($t\,ha^{-1}$) depends on ecosystem services provided by biodiversity (Fig. 1; Tscharntke et al., 2012). Such ecosystem services originate in the crop area itself or from surrounding (semi-) natural ecosystems (Holland et al., 2017; Tscharntke et al., 2005).

Although the variety of regulating services from which agriculture can benefit is large, three of them are recognized as highly influential: biotic pest regulation, pollination, and nutrient cycling (Power, 2010). Pest regulation relies on wild arthropod predators and parasitoids, insectivorous birds and bats, and microbial pathogens that act as natural enemies of agricultural pests (Tscharntke et al., 2005). Biotic pollination relies mainly on bees, but also on other animals such as syrphid flies and vertebrates (Potts et al., 2016). Nutrient cycling and soil formation (here referred to nutrient cycling for brevity) relies on many different services provided by bacteria, fungi, meso- and macro-fauna for fragmenting and decomposing organic matter, carbon sequestration, nitrogen fixation and nitrification, and reducing nutrient leaching (Power, 2010). Moreover, such biotic activity improves aeration of soils and soil pore structure, which are fundamental to nutrient acquisition by crops (Power, 2010).

There is an increasing recognition that regulatory services may interactively affect crop yield (Lundin et al., 2013; Sutter and Albrecht, 2016; van Gils et al., 2016). A positive interaction (synergism) between regulating services would mean that, for example, the effect on crop yield from pest regulation is higher with greater pollination (Fig. 2) (Lundin et al., 2013; Sutter and Albrecht, 2016). In contrast, a negative interaction would mean that the beneficial effect on crop yield from pest regulation is lower, but not necessarily negative, with greater pollination (Fig. 2). No interaction can imply additive effects (also known as complementary or independent effects) of pest regulation and pollination on crop yield, but it can also mean that only pollination or only pest regulation has an effect on crop yield. To date, questions remain in what ways regulatory services interact, which type of interaction is more common, and how such interactions can improve crop yields. Furthermore, it is unclear whether several ecosystem services limit crop yield simultaneously ("multiple limitation hypothesis") or crop yield is limited by the ecosystem service provided in the shortest supply relative to demand ("Liebig's law of the minimum") (Gleeson and Tilman, 1992; Rubio et al., 2003; Sperfeld et al., 2012). Therefore,

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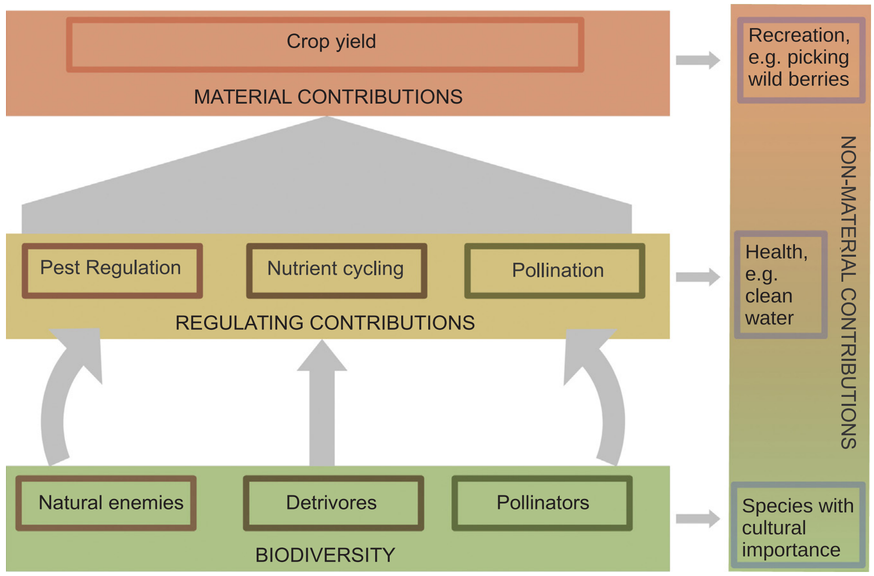

Fig. 1. Biodiversity supports crop yield through combined contributions of regulating ecosystem services and their interactions, and also provides non-material contributions to human wellbeing.

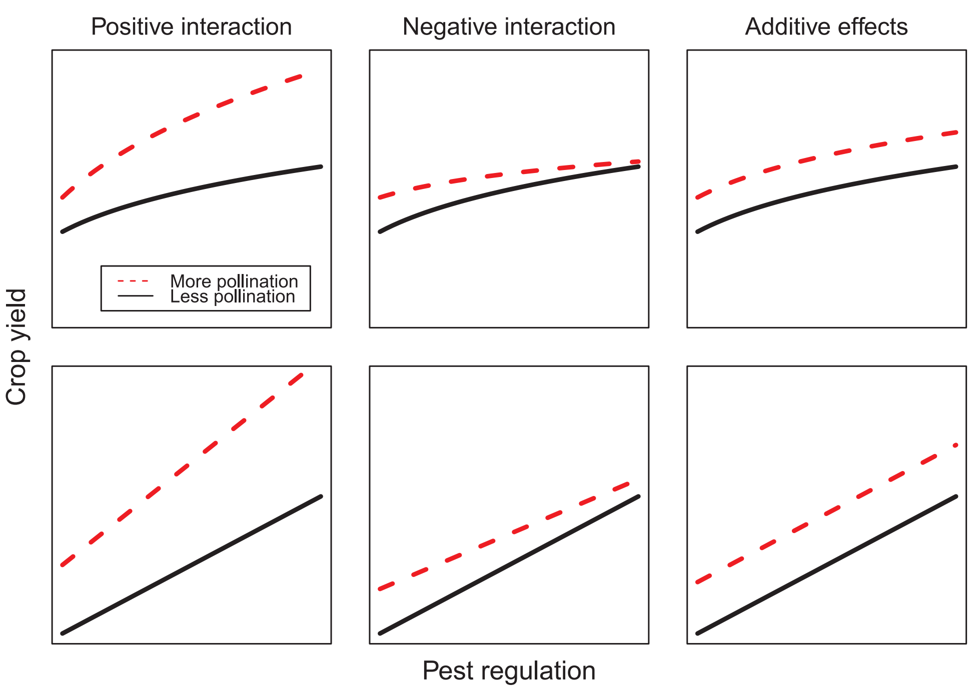

Fig. 2. Examples of positive interactions, negative interactions, and additive effects between regulating services to crop yield. Biotic pest regulation and pollination are exemplified for non-linear (top row) and linear (bottom row) relations. Most studies evaluate only two levels of regulating services, which do not allow quantification of the functional response form of crop yield to resources. Although the functions that are often theorized for such relation are non-linear (e.g. power, Michaelis-Menten, and negative exponential), the few studies available assume linear relations. The examples in this figure assume that crop yield is limited simultaneously by several regulating services (i.e. multiple limitation hypothesis).

here we review how biotic pest regulation, pollination, and nutrient cycling interact to support crop yield (Fig. 1).

2. Evidence for interactions among regulating services

We performed a three-step approach to find evidence for interactions among regulating services. We first searched for studies on Google Scholar with the search strings: (1) "pest regulation" AND "pollination" AND "crop yield" AND "interaction", (2) "pest regulation" AND "nutrient cycling" AND "crop yield" AND "interaction", and (3) "pollination" AND "nutrient cycling" AND "crop yield" AND "interaction". We repeated each search string with alternative search terms for pest regulation (biological control and pest control), for crop yield (agricultural production and crop production), and for nutrient cycling (agricultural management, soil fertility, soil organic carbon/matter). The first 200 results of each search string were carefully reviewed on the presence of crop yield measurement and if an interaction between the regulating services was tested. We excluded three studies using insecticide as the main pest regulation treatment (Adler and Hazzard, 2009; Melathopoulos et al., 2014; Motzke et al., 2015), because this affects not only the pests, but also the natural enemies and pollinators. Moreover, as we focus on agricultural crops, we excluded one study concerning cut roses (Chow et al., 2009). In this step we found 12 studies. In a second step we reviewed the references of these 12 studies, which yielded two additional studies. Lastly, in the third step we sought for additional studies not found in the first two steps, based on expert knowledge of the co-authors. This resulted in two additional, recently published studies, and made a total of 16 studies providing 20 analyses of the two-way interactions between biotic pest regulation, pollination, and nutrient cycling on crop yield (Table 1).

The interactions most frequently evaluated were between pollination and nutrient cycling (nine analyses) and between pollination and