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Habitat management on multiple spatial scales can enhance bee pollination and crop yield in tropical homegardens

Iris Motzke[a,b,*], Alexandra-Maria Klein[b,c], Shahabuddin Saleh[d], Thomas C. Wanger[a,c,e], Teja Tscharntke[a]

[a] Department of Crop Sciences, Agroecology, Georg-August-University Göttingen, Grisebachstr. 6, 37077 Göttingen, Germany
[b] Nature Conservation and Landscape Ecology, Institute of Earth and Environmental Sciences, University of Freiburg, Tennenbacher Str. 4, 79106 Freiburg, Germany
[c] Institute of Ecology, Ecosystem Functions, Leuphana University Lüneburg, Scharnhorststr. 1, 21335 Lüneburg Germany
[d] Department of Agrotechnology, Faculty of Agriculture, University of Tadulako, Palu 94118, Central Sulawesi, Indonesia
[e] Department of Ecology, Swedish University of Agricultural Sciences, 75007 Uppsala, Sweden

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ABSTRACT

Pollinator populations respond to environmental changes operating on different spatial scales, but the contribution of scale-dependent habitat management to crop pollination and yield-gap reduction is little understood. Here, we analyze how bee abundance and their effects on cucumber production in tropical homegardens is driven by factors measured on three spatial scales; the (1) homegarden scale (flower cover of the focal homegarden); the (2) adjacent-habitat scale (amount of homegarden habitat within a 200 m radius around the focal homegarden); and the (3) landscape scale (distance of the focal homegarden to the nearest forest from 0 to 2200 m). We also evaluate bee responses according to functional traits such as body size.

We found that bees were affected by factors on multiple spatial scales. On the homegarden scale, the percentage flower cover best predicted pollinator attraction, if, on the adjacent-habitat scale the percentage of surrounding homegardens was at least 20%. On the landscape scale, bee abundance, mainly of small species, increased when homegardens were closer to the forest.

Increasing abundance of flower-visiting bees increased cucumber yield, with solitary bees being the most abundant flower visitors. We predicted that a 50% loss in bee abundance would translate into a 47% yield and associated income decline. Homegardens with a flower cover of 50%, being surrounded by a homegarden area of 50% and being established <100 m from the forest can translate in a nine-fold higher yield and income compared to homegardens with low flower cover (<15%), and isolated from other homegardens (<20%) and the forest (>1500 m).

Our work suggests that farmers need to be aware of management practices not only at the local and landscape scale but also on the adjacent-habitat scale. Only then farmers can increase wild bee populations to reduce crop yield gaps through pollination services.

1. Introduction

Insect pollinators provide an economically important service for crop production and human health (Klein et al., 2007; Smith et al., 2015) but this service is at risk (Aizen et al., 2008) due to declining bee populations in Europe and the US (Kosior et al., 2007; Potts et al., 2010; Cameron et al., 2011; Gonzalez-Varo et al., 2013). Several studies have investigated the impact of environmental factors shaping the habitat of managed and wild pollinators at local and landscape scales (e.g., Kennedy et al., 2013; Rader et al., 2016). But in tropical areas, where farmers often depend on wild, non-managed bees (Klein et al., 2003a; Hoehn et al., 2008), studies on habitat management practices at local habitat, adjacent-habitat and landscape scales that affect wild pollinators and pollination services are still underrepresented (but see for example Klein et al., 2008; Carvalheiro et al., 2011; Krishnan et al., 2012; Boreux et al., 2013). Research, hence, needs to address the drivers of diversity

* Corresponding author.
E-mail addresses: Iris.Motzke@posteo.de (I. Motzke), alexandra.klein@nature.uni-freiburg.de (A.-M. Klein), shahabsaleh@gmail.com (S. Saleh), tomcwanger@gmail.com (T.C. Wanger), ttschar@gwdg.de (T. Tscharntke).

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and flower-visiting abundance of wild bees on different spatial scales in tropical landscapes (Tscharntke et al., 2005, 2012).

Wild bee populations can be influenced by multi-scale determinants through (i) local management practices including provision and availability of alternative flower resources (*local* or in our case the *homegarden scale)*, (ii) availability of quality habitat in the direct neighborhood (*adjacent-habitat scale*), and (iii) isolation from natural habitat (*landscape scale*; Kremen et al., 2007; Carvalheiro et al., 2011; Kennedy et al., 2013). On the *local scale,* habitat management can have a great influence on wild bees and pollination services, often in interaction with (e.g., Rundlöf et al., 2008; Williams and Kremen, 2007; Concepcion et al., 2012) and sometimes more important than landscape scale effects (Jha and Vandermeer, 2009; Kennedy et al., 2013). Pollinator populations are attracted to the farm by high flower resources of both crop and non-crop flowers on the farm from the surrounding landscape such as homegardens adjacent to the farm (e.g., Kim et al., 2006; Holzschuh et al., 2008; Batáry et al., 2011). On the *adjacent-habitat scale*, the amount of natural or semi-natural habitat adjacent to crops as source habitat can increase the available species pool (Tscharntke et al., 2012). *Local* and *adjacent habitat* does not necessarily have to be natural habitat; for example, homegardens can act both as important habitats for bees, depending on the amount of food and nesting resources offered (Goulson, 2003; Smith et al., 2006; Cussans et al., 2010; Samnegård et al., 2011). On the *landscape scale*, the increasing distance to the nearest natural habitat can negatively affect bee abundance and richness, because natural habitats provides essential resources for many bee species (Garibaldi et al., 2011) and determines the access of bees to the target crops (Tscharntke et al., 2012). However, a size limitation of the available species pool can be more important than the distance to natural habitat (Schüepp et al., 2014).

Patterns of bee–flower–yield interactions are usually driven in a complex way, and most local and landscape variables do not act separately but are influenced by each other (Brittain et al., 2010; Andersson et al., 2013; Schüepp et al., 2014). Further, differences between pollinator guilds (Greenleaf and Kremen, 2006; Rundlöf et al., 2008) play a role. Scale-dependency may change between solitary and social bees (e.g., Klein et al., 2003b) and with body size (e.g., Klein et al., 2008). For example, small bees might respond at finer scales than large bees due to their smaller foraging distances (Gathmann and Tscharntke, 2002; Greenleaf et al., 2007; Klein et al., 2008; Benjamin et al., 2014).

It is important to include the relation of habitat management and pollinator visitation to yield and farmers' income, which then highlights the direct benefits of pollination to farmers (e.g., Holzschuh et al., 2007; Rundlöf et al., 2008; Blaauw and Isaacs, 2014). Enhancing bee populations and flower visitation are only intermediate services, whereas the improved crop yield is the final service and the direct benefit to farmers (e.g., Holzschuh et al., 2007; Rundlöf et al., 2008). Disentangling the interacting effects of factors and processes operating on different spatial scales for the explanation of crop yield changes is necessary and may provide better cost-benefit analyses of landscape and farm management practices (e.g., Greenleaf and Kremen, 2006; Carvalheiro et al., 2010; Boreux et al., 2013; Schüepp et al., 2014). Here, we determine the interactive effects of habitat management for bees on three spatial scales in a homegarden-forest landscape in Indonesia. Specifically, we investigate how landscape, adjacent-habitat, and farm scale management influences the abundance of bees visiting pollinator-dependent cucumber flowers and finally, the yield and income of tropical smallholders.

2. Methods

2.1. Study area and crop system

Our study was conducted in Lore Utara (Napu valley), Central Sulawesi, Indonesia. The valley is located between Palu city and Poso regency at an elevation of 1100–1200 m a.s.l. with mean annual temperatures of 24.0 ± 0.16 °C. The area comprises a mosaic of villages with species-rich traditional homegardens embedded in rice paddies, vegetable plantations (mostly monocultural fields), and cacao agroforests directly bordering the tropical rainforest of the Lore Lindu National Park. Due to high human immigration and a strongly growing human population, illegal deforestation, and pollution from pesticide use are challenging the environment (Maertens et al., 2002; Kehlenbeck, 2007; Wanger et al., 2010). The area is well known for their diverse traditional homegardens (Kehlenbeck and Maass, 2006), which provide heterogeneous habitats (with blooming patches, fallows, woody plants and undisturbed soils; Kehlenbeck, 2007), offering food and nesting resources for bees as well as a refuge from pollution and land conversion. These homegardens play an important role for both subsistence and cash income (Kehlenbeck and Maass 2006).

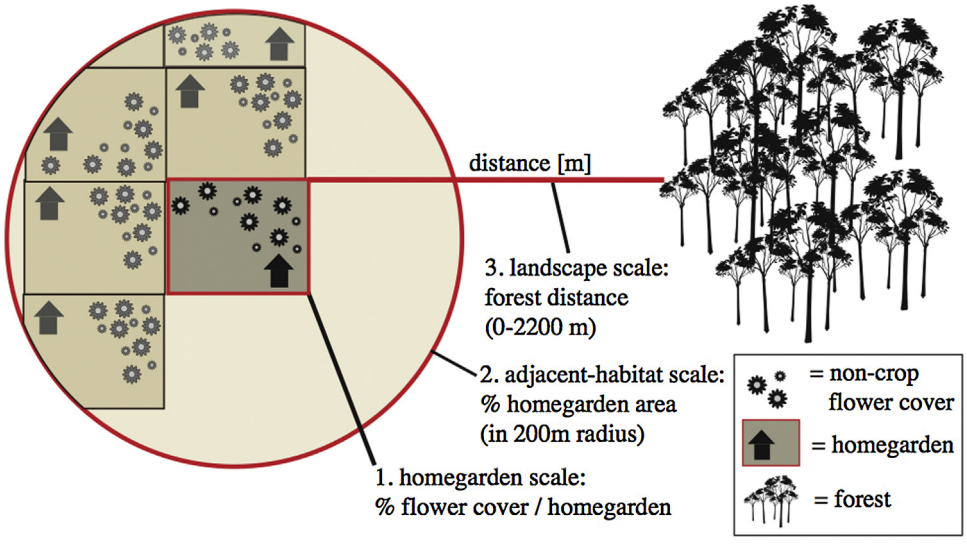

Fig. 1. Schematic figure of the three spatial scales assessed in this study. Spatial scales increase from the homegarden, to the adjacent-habitat, and to landscape scale.