Does the dilution effect generally occur in animal diseases?

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SUMMARY

The dilution effect (DE) has been reported in many diseases, but its generality is still highly disputed. Most current criticisms of DE are related to animal diseases. Particularly, some critical studies argued that DE is less likely to occur in complex environments. Here our meta-analyses demonstrated that the magnitude of DE did not differ between animal *vs* plant diseases. Moreover, DE generally occurs in all three subgroups of animal diseases, namely direct-transmitted diseases, vector-borne diseases and diseases caused by parasites with free-living stages. Our findings serve as an important contribution to understanding the generality of DE.

Key words: Diversity–disease relationship, host species diversity, vector-borne disease, direct-transmitted disease, parasite with free-living stage.

INTRODUCTION

Host diversity has been postulated to influence transmission risk of infectious diseases (Johnson & Thieltges, 2010; Keesing *et al*. 2010, 2006). In theory, increase in host diversity in communities can either amplify or reduce pathogen transmission through mechanisms such as regulating the abundance of competent hosts or altering the contact rates among competent hosts/vectors (Keesing *et al*. 2006). The dilution effect (DE hereafter) hypothesis, in which high host species diversity can reduce disease risk, has been reported in a wide range of infectious disease systems (Allan *et al*. 2009; Johnson *et al*. 2009; Pongsiri *et al*. 2009; Suzán *et al*. 2009; Keesing *et al*. 2010; Ostfeld & Keesing, 2012; Huang *et al*. 2013*a*; Johnson et al. 2013; Huang *et al*. 2016). This negative diversity–disease relationship, representing an exciting convergence of conservation and public health interests (Randolph & Dobson, 2012; Young *et al*. 2013; Wood *et al*. 2014), has attracted much attention in the context of global biodiversity decline and increasing disease emergence (Ostfeld & Keesing, 2012; Randolph & Dobson, 2012; Wood *et al*. 2014; Huang *et al*. 2016). However, recent studies started criticizing the generality of DE and considered that the DE is idiosyncratic and only occurs under certain conditions (Randolph & Dobson, 2012; Salkeld *et al*. 2013; Wood & Lafferty, 2013; Young *et al*. 2013; Wood *et al*. 2014). Better understanding the generality of DE will be critical for predicting future disease outbreaks especially in the condition of ongoing biodiversity decline (Keesing *et al*. 2006; Ostfeld & Keesing, 2012).

When retrospecting the recent critical studies (Cardinale *et al*. 2012; Randolph & Dobson, 2012; Salkeld *et al*. 2013; Wood & Lafferty, 2013; Young *et al*. 2013; Wood *et al*. 2014), we found an interesting phenomenon that almost all current criticisms of DE are related to animal diseases, while those for plant diseases are conspicuously rare. A recent meta-analysis study has presented evidence for the DE in various functional groups of parasites, and intended to put a closure to the current debate (Civitello *et al*. 2015). However, their conclusion remains provisional without addressing the important distinction in plant *vs* animal diseases. Addressing the question whether the DE is generally weaker in animal diseases than in plant diseases will be fundamental to understand the generality of the DE.

The occurrence of the DE has been attributed to two main mechanisms in diverse communities: (1) susceptible host regulation leading to lower abundance of competent hosts in high-diversity communities due to predation or competition by low-competence hosts and (2) encounter reduction due to the reduction of the contact rates among competent hosts or between competent hosts and vectors in the presence of low-competence hosts (Keesing *et al*. 2006). Susceptible host regulation has been found in many diseases, including both animal diseases and plant diseases. However, the meta-analysis by (Civitello *et al*. 2015) did not find an association between host density and the strength of the DE, indicating that this susceptible host regulation does not operate in all studied diseases.

For plant diseases, low-competence hosts surrounding competent hosts can act as physical

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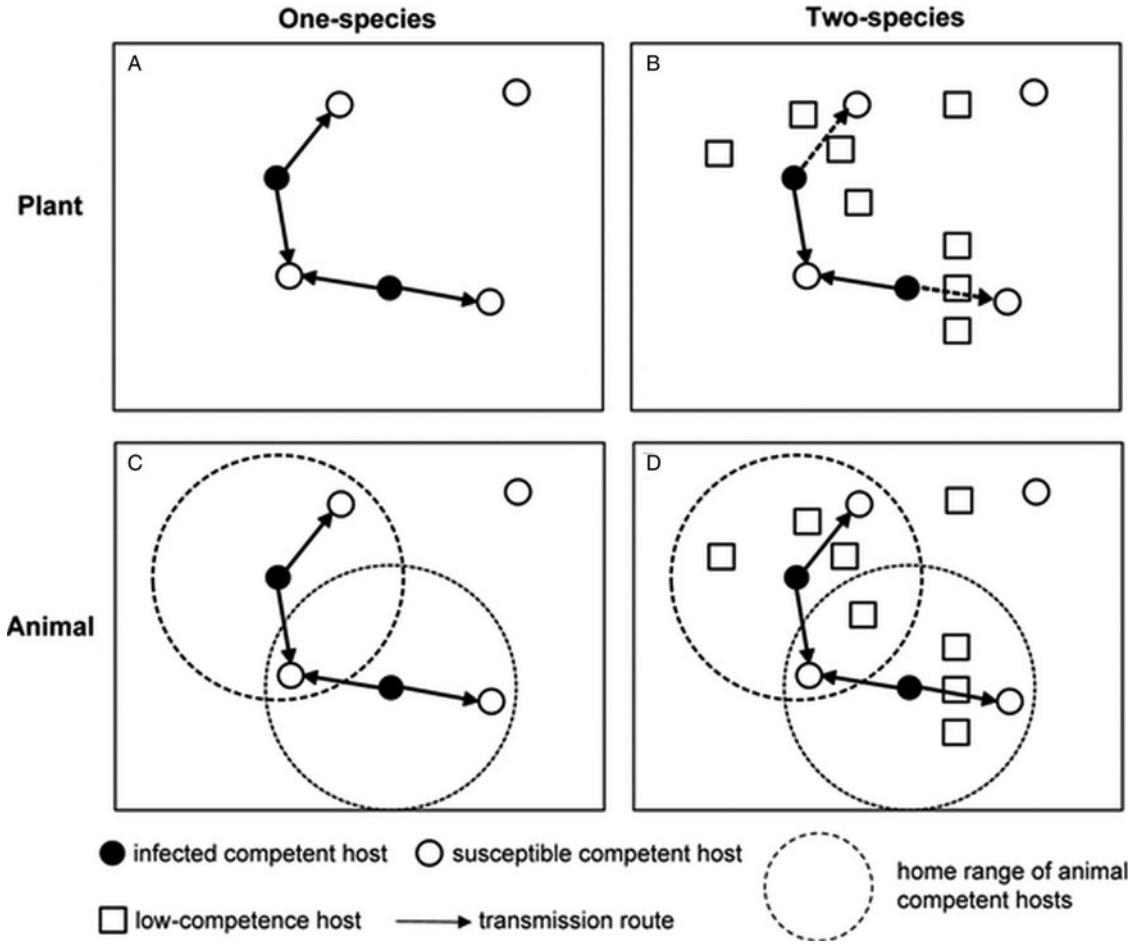

Fig. 1. Difference in mobility between plants and animals might explain the difference in effectivity of the barrier effect of low-competence hosts on disease risk in plant diseases (A, B) and animal diseases (C, D). Both the original plant community (A) and the original animal community (B) consist of a single competent host species with some individuals infected (filled circles) and some individuals uninfected and therefore susceptible (open circles). Each animal individual uses a particular home range (dashed lines). Pathogens can transmit, either through direct transmission or via vector/wind borne transmission, from infected individuals to susceptible individuals (arrows indicate directions). In plant diseases, the addition of low-competence hosts (open squares) can act as physical barriers for pathogen spread (B, dashed arrows). While in animal diseases, the barrier effect of low-competence hosts might be ineffective as animal can move (D).

barriers, interfering with the transmission pathways and thus inhibiting the spread of parasites or vectors (Fig. 1). This mechanism could be considered as a kind of encounter reduction that decreases the chance of the spread of parasites (or vectors carrying pathogens) from one competent host to another. This barrier effect of low-competence hosts, however, may be ineffective in animal diseases as animals are mobile, and the movement distance of animal hosts is often larger than that of the parasites and/or vectors (Fig. 1). We expect that the difference in mobility between plants and animals might be one of the reasons for the imbalance of previous criticisms on the DE in plant and animal diseases. In addition, animals are found to be able to select habitat where infection risk is low (Moore, 2002), reducing disease prevalence. Therefore, the risk of being infected can depend on mobility, which also asks for a comparison of the role of the DE in plant and animal communities.

MATERIALS AND METHODS

Here we extracted the dataset from (Civitello *et al.* 2015), and tested whether the mean effect of host diversity on disease abundance differs between animal and plant diseases. In addition, a previous study argued that the DE may occur more frequently in relatively simple systems, but are less common in complex environments that are typical of many vector-borne diseases and diseases caused by parasites with free-living stages (Randolph & Dobson, 2012; Johnson *et al.* 2015). We thus further divided animal diseases into three subgroups, and test whether the mean effect of host diversity on disease abundance differs between

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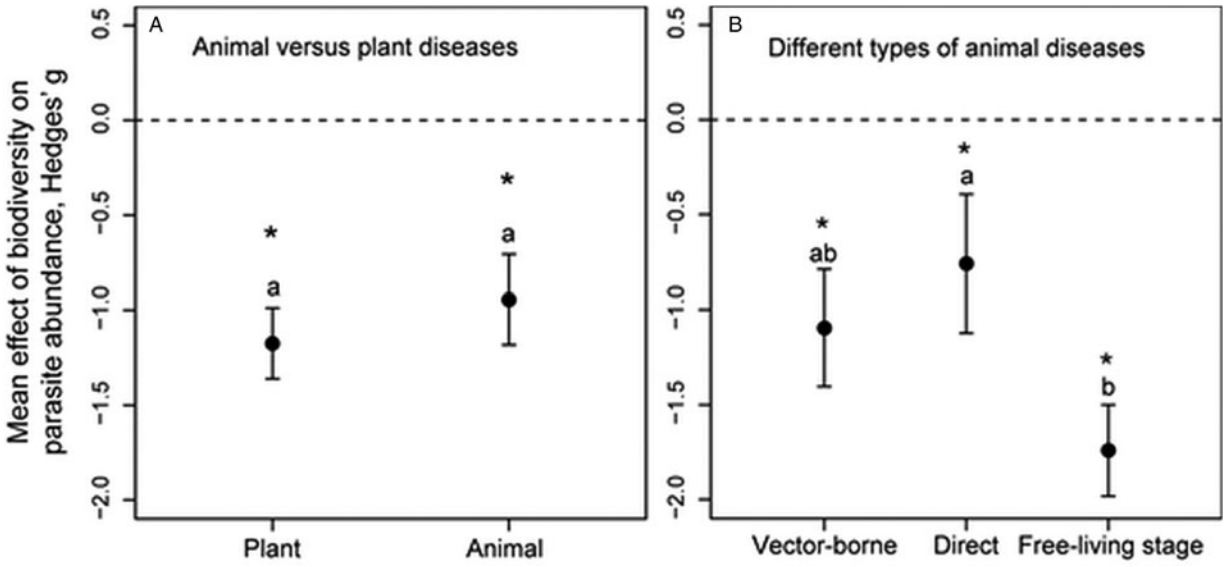

Fig. 2. Results of the meta-analysis of the generality of the dilution effect hypothesis in (A) plant diseases ($n = 104$) *vs* animal diseases ($n = 98$); (B) animal vector-borne diseases ($n = 15$), animal direct-transmitted diseases ($n = 26$) and animal diseases caused by parasites with free-living stages ($n = 57$). Asterisks indicate significant ($P < 0{\cdot}05$) differences from zero. Error bars represent ± S.E. Different lowercase letters indicate significant differences in the mean effect of biodiversity on parasite abundance between subgroups.

three subgroups. We here applied a multilevel random-effects meta-analysis model as used in (Civitello *et al*. 2015), in which Hedges' g statistic was taken as the measure of effect size.

RESULTS AND DISCUSSION

Our results showed a strong negative mean effect of host diversity on both plant diseases ($g = -1{\cdot}18 \pm 0{\cdot}19$ S.E., $P < 0{\cdot}001$) and animal diseases ($g = -0{\cdot}94 \pm 0{\cdot}24$ S.E., $P < 0{\cdot}001$), but the magnitude of the DE did not differ between these two groups ($P = 0{\cdot}44$, Fig. 2A). By comparing three subgroups of animal diseases, we found a negative mean effect in all direct-transmitted diseases, vector-borne diseases and diseases caused by parasites with free-living stages (Fig. 2B). There was a stronger DE in animal diseases caused by parasites with free-living stages than in direct-transmitted diseases.

These results lead to the critical question how the DE operates in animal diseases. Although the barrier effect of low-competence hosts is still discussed for animal diseases (Fig. 1), there are still other kinds of mechanisms causing the encounter reduction. It indeed has been found that the contact rates among competent hosts can also be suppressed by the low-competence hosts in some direct-transmitted animal diseases, such as bovine tuberculosis (Huang *et al*. 2013*b*) and Hantavirus (Clay *et al*. 2009). Studies regarding these diseases usually suggest that the reduced contact rates between competent hosts may result from changed foraging or movement patterns in the presence of low-competence hosts (Clay *et al*. 2009; Huang *et al*. 2013*b*). However, these assumptions usually lack empirical evidence, and thus more effort is needed to explore the underlying biological reasons. In vector-borne diseases, the low-competence hosts can extract vectors away from the competent hosts and thus reduce the contact rates among vectors and competent hosts (Keesing et al. *2006*). This mechanism, similar as that in zooprophylaxis in the case of malaria where domestic animals are used near a house to attract mosquitoes away from humans and reduce the malaria risk in humans (Keesing *et al*. 2006; Randolph & Dobson, 2012), could also be considered as a kind of encounter reduction mechanism. Finally, in animal diseases caused by parasites with free-living stages, low-competent hosts (or dead-end hosts) can serve as sinks and extract parasites away from competent hosts, reducing the contact rate between parasites and competent hosts. Hence, encounter reduction mechanism can also operate in these diseases, especially when parasite abundance is limited (Johnson & Thieltges, 2010). We here found an even stronger DE in animal diseases caused by parasites with free-living stages. This could be caused by the fact that having a free-living stage essentially allows for an additional opportunity of predation, death, or other loss of the parasite.

We demonstrate that host diversity generally inhibits pathogen transmission in both plant and animal diseases. Our results, which conflict with previous criticisms to the application of the DE in animal diseases (Cardinale *et al*. 2012; Randolph & Dobson, 2012), serve as an important contribution to understanding the generality of the DE. Although the

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barrier effect of the incompetent hosts may not apply to animal diseases, the encounter reduction can still operate through other mechanisms. We also suggest that more research efforts are required to explore the underlying biological reasons for the encounter reduction.

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AUTHOR CONTRIBUTIONS

Z.Y.X.H. and Y.Y. analysed data; Z.Y.X.H., Fv.L., and W.F.dB. wrote the paper. The authors declare no conflict of interest.

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