

The temporal assembly of plant-pollinator networks following restoration

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Abstract

TO BE RE-WRITTEN The structure of networks is related to ability of communities to maintain function in the face of species extinction. Understanding network structure and how it relates to network disassembly, therefore, is a priority for system-level conservation biology. We explore the assembly of plant-pollinator communities on native plant restorations in the Central Valley of California. The assembling communities are paired with unrestored field margins (controls) and mature (non-assembling) hedgerows. We determine whether there are change points in the assembly of the communities where the network undergoes significant reorganization. We are also ask how are the individual species changing their interaction patterns? What does this mean for the topology/resilience of the network? We also attempted to adapt a financial model to mutualistic networks. Our biggest difficulty with this approach was to translate the price term to mutualistic systems. We explored a range of approaches, such as number of visits a species performs. However, it seems that financial systems cannot be easily translated to mutualistic systems. In addition, we used a Changing Point Detection Algorithm to assess weather the different communities went through a critical reorganization on their interaction patterns. We were able to identify some changing points in the communities, and also to explore some general patterns commonly used to describe ecological networks. For example, on the network level, networks become increasingly modular and less nested, whereas on the species level, species become more specialized, as resources become more reliable.

Keywords: changing points, temporal networks, hedgerows, species interactions, preferential attachment, mutualisms

Introduction

Global change has created a severe biodiversity crisis, and as species are lost, so are their interactions (Dunn *et al.*, 2009; Barnosky *et al.*, 2011). Because mutualistic interactions are essential for maintaining the diversity their component guilds of species, these systems are particularly at risk from coextinction cascades. The nature of these coextinction cascades depends on the interaction patterns within a community (Memmott *et al.*, 2004; Rezende *et al.*, 2007; Bascompte & Stouffer, 2009). Recovering the lost biodiversity and interactions through ecological restoration has become increasingly imperative, and a key restoration aim is to facilitate assembly of robust interaction networks (Menz *et al.*, 2010). We know little, however, about how to re-assemble interacting communities through restoration, or the process of ecological network assembly more generally.

The mostly widely explored mechanism of network assembly, preferential attachment (Barabási & Albert, 1999), predicts that a new species is more likely to interact with species that are already well-connected ("the rich-get-richer" principle, Barabási & Albert, 1999). In pollination systems — a particularly ubiquitous mutualism (Ollerton *et al.*, 2011; Klein *et al.*, 2007) — some studies have found support for this mechanism of assembly. Investigating the day-to-day, temporal assembly of a plant-pollinator network within a season, Olesen *et al.* (2008) found that new species tended to interact with already well-connected species, likely because these species are either more abundant or more temporally persistent (Olesen *et al.*, 2008). In addition, using a space-for-time substitution to study primary succession along a glacier foreland, Albrecht *et al.* (2010) found some indication assembly was occurring through preferential attachment. Network nestedness, a pattern of interactions where a generalist core interacts with both specialist and generalist species, increased as the community aged (Albrecht *et al.*, 2010). Increasing nestedness could result from a process like preferential attachment where specialist species attach to the well-

connected, generalist core.

In contrast to the ordered network build-up described by preferential attachment, assembly can be punctuated by significant reorganizations of interactions (Peel & Clauset, 2014). For example, as new species are added, resident species change their interaction partners to minimize competition, or become extinct. Such significant reorganizations of interactions, or changing points, have been observed in networks responding to abrupt shifts in the behavior of interactors (Peel & Clauset, 2014). No studies, however, have examined whether changing points occur during ecological network assembly.

Understanding network assembly is particularly relevant to ecological restoration, which is essentially 'applied succession' (Parker, 1997, e.g.). In pollination systems, the time since an area was restored has been shown to effect the structure of networks (Forup *et al.*, 2008a,b; Devoto *et al.*, 2012), suggesting interactions are evolving as the community develops. Understanding the mechanisms of network assembly will help to guide the restoration of particular communities.

Facilitating effective restoration of networks is particularly imperative in areas where species interactions provide essential ecosystem services, such as crop pollination. In intensively managed agricultural landscapes, the demand for pollination services is the greatest (Kremen, 2008). However, honey bees, managed extensively around the world to provide crop pollination, are in global decline (Neumann & Carreck, 2010; van Engelsdorp *et al.*, 2009). In addition, native pollinators, which have the capacity to provide sufficient crop pollination (Kremen *et al.*, 2002; Winfree *et al.*, 2007; Kremen *et al.*, 2004), are in short supply because these landscapes make poor habitats for pollinator populations (Kremen *et al.*, 2002). To ensure provision the continued provision of ecosystem services and curb biodiversity loss, effective restoration of pollinators and their interactions in agricultural landscapes is critical.

To promote pollinator services in agriculture, farmers are increasingly turning to the habitat restoration technique of planting strips of native plants along farm edges (hedgerows) to help provide habitat for pollinators without removing arable land from production. Hedgerows have been shown to augment the richness, abundance and trait diversity of pollinators in agricultural landscapes (Morandin & Kremen, 2013; M'Gonigle *et al.*, 2015; Kremen & M'Gonigle, 2015; Ponisio *et al.*, 2015). In addition, hedgerows promote the persistence and colonization of floral resource specialists (M'Gonigle *et al.*, 2015). Little is known however, about the assembly of the network following hedgerow restoration.

Using a long-term data-set of plant-pollinator communities assembling following hedgerow restoration in the highly simplified and intensively managed agricultural landscape of California's Central Valley, we explore the process of network development. We first determine whether the mechanism underlying network assembly is a smooth build up of interactions as would be predicted by preferential attachment, or punctuated by significant reorganizations of interactions (i.e., changing points). Even with changing points in interaction organization, networks could still be assembling via preferential attachment if the network reorganizations were primarily driven by peripheral, temporally variable species while a stable, well-connected core of species still persists. We thus examine whether the species are most variable in their network position — and thus important contributors to network reorganizations — are less persistent and connected species. Lastly, we examine whether networks are assembling toward predictable interaction patterns, and the ramifications for the robustness of the networks to species extinction and perturbation.

Materials & Methods

Study sites and collection methods

We surveyed plant-pollinator interaction networks of assembling hedgerows (N=5), as well as in two types of non-assembling communities to serve as controls: unrestored, weedy field margins (N=XX) and established hedgerows (greater than 10 years since planting, N=XX). The sites were located in the Central Valley of California in Yolo, Colusa and Solano Counties. This area is comprised of intensively managed agriculture – primarily monocultures of conventional row crops, vineyards and orchards. Hedgerows we planted along field margins where they do not remove valuable land from production, and are ca. 3–6m wide and approximately 350m long and border large (ca. 30–hectare) crop fields. Hedgerows consist of native, perennial, shrub and tree plantings including *Rosa californica*, *Cercis occidentalis*, *Ceanothus spp.*, *Heteromeles arbutifolia*, *Sambucus mexicana*, *Eriogonum spp.*, *Baccharis spp.*, *Salvia spp.* and others (Kremen & M’Gonigle, 2015; M’Gonigle *et al.*, 2015). The mean distance between monitoring sites was 15 km, and the minimum distance between sites of the same type sampled in the same year was 2 km. The entire area surveyed spanned almost 300 km². The crop fields adjacent to all sites were similarly managed as intensive, high-input monoculture.

Monitoring began in 2006 and continued through 2015. Sampling of the assembling hedgerows began the year before the area was restored. For logistical reasons, no sampling of assembling hedgerows was conducted in 2010. Sites were sampled between two and five times per year (Table XX). In each round of sampling, the order in which sites were sampled was randomized. Surveys were conducted under sunny conditions when the temperature was above 21°C and wind speed was below 2.5 meters/second.

Flower-visitors to plants in hedgerows and unrestored controls were netted for one hour of active search time (the timer was paused when handling specimens). Honeybees (*Apis mellifera*) were not collected because their abundance is determined largely by the placement of hives throughout the region by bee-keepers. All other insect flower visitors that touched the reproductive parts of the flower were collected; however, here we focus only on wild bees and syrphids (representing XX and XX percent of records, respectively), the most abundant and effective pollinators in the system (C. Kremen, A. Klein and L. Morandin, unpublished data). Bee and syrphid specimens were identified to species (or morpho-species for some bee specimens in the genera *Nomada* and *Sphecodes*) by expert taxonomists.

Quantitative networks were generative for each site through time. To account for the unequal number of surveys between years, the mean of the interactions between a pair of plants and pollinators across surveys within a year was used as a representation of the frequency of interactions.

Change point analysis

Identifying change points

We employed a change point detection method (Peel & Clauset, 2014) to identify fundamental changes in large-scale pattern of interactions of plants and pollinators. A change point is caused by a merge, split, fragmentation or formation of communities (also called modules or compartments). Change point detection methods have yet to be generalized to quantitative networks, so for this analysis we focused on qualitative (binary) networks. Following Peel & Clauset (2014), we first defined a probability distribution over the networks using the generalized hierarchical random graph model (GHRG). The

GHRG model is able to capture both assortative and disassortative community structure patterns at all scales in the network (Peel & Clauset, 2014). A network G is composed of vertices V and edges $E \subseteq VV$. The GHRG model decomposes the N vertices into a series of nested groups, the relationships among which are represented by the dendrogram T . The tips of T are the vertices of G , and the probability that two vertices u and v connect is given by the parameter p_r . The probability distribution of the network G thus defined as:

$$P(G|T, pr) = p_r^{E_r} (1 - p_r)^{N_r - E_r} \quad (1)$$

Where E_r is the observed number of edges between vertices with the common ancestor r , and N_r is the total possible edges.

Using Bayesian posterior inference and techniques from phylogenetic tree reconstruction, we fit the GHRG model to the networks (Peel & Clauset, 2014). This is accomplished by using a Markov Chain Monte Carlo (MCMC) procedure to first sample the posterior distribution of bipartitions, from which a consensus tree is derived (Peel & Clauset, 2014). We used β distributions with the hyperparameters $\alpha = \beta = 1$ to define priors for p_r .

Once the GHRG model has been fit to the networks, we determine whether a change point occurred between two time slices. To detect a change point, we compare the fit of two models – one where a change point had occurred between two networks, and one where no change occurred – using posterior Bayes factors. We chose a sliding window of length, w , of four, within which to find change points. Larger windows allow for more gradual changes, and four was the maximum possible with our maximum of nine years of data. Lastly, to calculate a p -value for the Bayes factors, we use parametric bootstrapping to numerically estimate the null distribution (Peel & Clauset, 2014). The change point

analysis was carried out using code published online by L. Peel.

We next test whether the change points occurring in maturing hedgerows were a component of the assembly process or a product of environmental shifts that lead to network reorganizations in all types of communities. We model the number of change points as successes and the total number of years each site was sampled as trials, and use a generalized linear model with Binomial error to test whether the probability of a change point occurring varied by site type. For the non-assembling hedgerows and weedy field margins, only sites with five or greater years of sampling was included in this analysis.

Characteristics of species that contribute to change points

To further elucidate the nature of the change points, we examine the characteristics of the species that contributed the reorganization of interactions. Some species remain in relatively similar network positions through time, whereas others are more variable in their role and thus contribute more strongly to network reorganization. We test the that more persistent species with the highest degree are the most stable in their network position, as would be expected is the networks were assembling via preferential attachment.

We calculate species persistence as the proportion of the surveys a pollinator was observed. Species observed consistently within and between years are thus maximally persistent. Weighted species degree is calculated from interaction observations observed in more extensive data-set from Yolo County (approx. 18000 interaction records) that included both the data included in this study and additional data from sites where we collected flower visitors using the same methods (M'Gonigle *et al.*, 2015; Ponisio *et al.*, 2015). To represent the the variability of species within networks, we computed the coefficient of variation of weighted closeness at each site through time. Closeness describes the centrality of a species in the network by calculating path lengths to other vertices

(species) in the graph. We used linear mixed models to test whether the variability of species closeness values was related to the persistence or degree of that species. We included random effects for species, as well as site. We focused on the pollinator species because the hedgerow flowers are planted and thus are not directly assembling. Because degree and persistence were strongly correlated, ($\rho = 0.84$, $p\text{-value} < 2 * 10^{-16}$), each explanatory variable was included in the model separately.

Temporal changes in interaction patterns

The changing points in network structure may contribute to the reorganization of the assembling networks into predictable interaction patterns. Pollination networks exhibit two main topologies — modularity (e.g., Olesen *et al.*, 2007) and nestedness (e.g., Bascompte *et al.*, 2006, 2003). Modular community interactions are insular, occurring within separate groups or “modules” more often than between modules. Communities in the network may fragment as the network assembles, enhancing modularity. Conversely, nested networks are like pyramid of interactions, where there are some species that interact with many species, other species that interact with a subset of those species, and so on. If species entering the network tend to interact with the generalist base of the network pyramid (i.e., preferential attachment), nestedness would increase through time. Lastly, if the network is accumulating specialist species or species are beginning to limit their interaction niche breadth as the network assembles, this would lead to an increase in the network-level specialization (Blüthgen *et al.*, 2006). To test whether network modularity, nestedness or specialization changed linearly with assembly, we used linear mixed models with the descriptive network metrics as the response variable, year of assembly as the explanatory variable, and random effects of site and year.

We use NODF (weighted or unweighted) to evaluate network nestedness (Almeida-Neto

et al., 2008). NODF evaluates whether species with fewer partners interact with subsets of partners with which more connected species interact (Almeida-Neto *et al.*, 2008). To estimate modularity, we use a hierarchical clustering algorithm (Newman & Girvan, 2004; Csardi & Nepusz, 2006). We calculated standardized z-scores so that nestedness and modularity metrics could be compared between communities. The z-scores were calculated by generating an ensemble of 999 randomly assembled communities, subtracting the mean of the statistic calculated across these communities from the observed value, and then dividing by the standard deviation. To assemble random communities, we reshuffled the interactions between species but fixed the total number of interactions, species and the distribution of the interaction frequencies (Galeano *et al.*, 2009). Lastly, Network specialization was measured using H2, which estimate the deviation of the observed interaction frequency between plants and pollinators from a null expectation where all partners interact in proportion to their abundances (Blüthgen *et al.*, 2006). It ranges from 0 for generalized networks to 1 for specialized networks.

Network robustness

Lastly, we test the changes in interaction patterns associated with network assembly affect the robustness. First, following Memmott *et al.* (2004), we simulate the extinction of plant species the subsequent extinction cascades of pollinator species. Because the reproduction of plant species if facilitated by active restoration efforts, it is unlikely the extinction of pollinators would effect plant populations in the hedgerows. However, plants ceasing to bloom, for example in response to drought, will likely effect the pollinators that depend on them. Plants species were eliminated based on their degree or abundance, and the number of pollinators that secondarily went extinct is calculated. The area below the extinction curve is used as a measure of network robustness (Memmott *et al.*, 2004).

237 **Results**

238 **Change point analysis**

239 **Identifying change points**

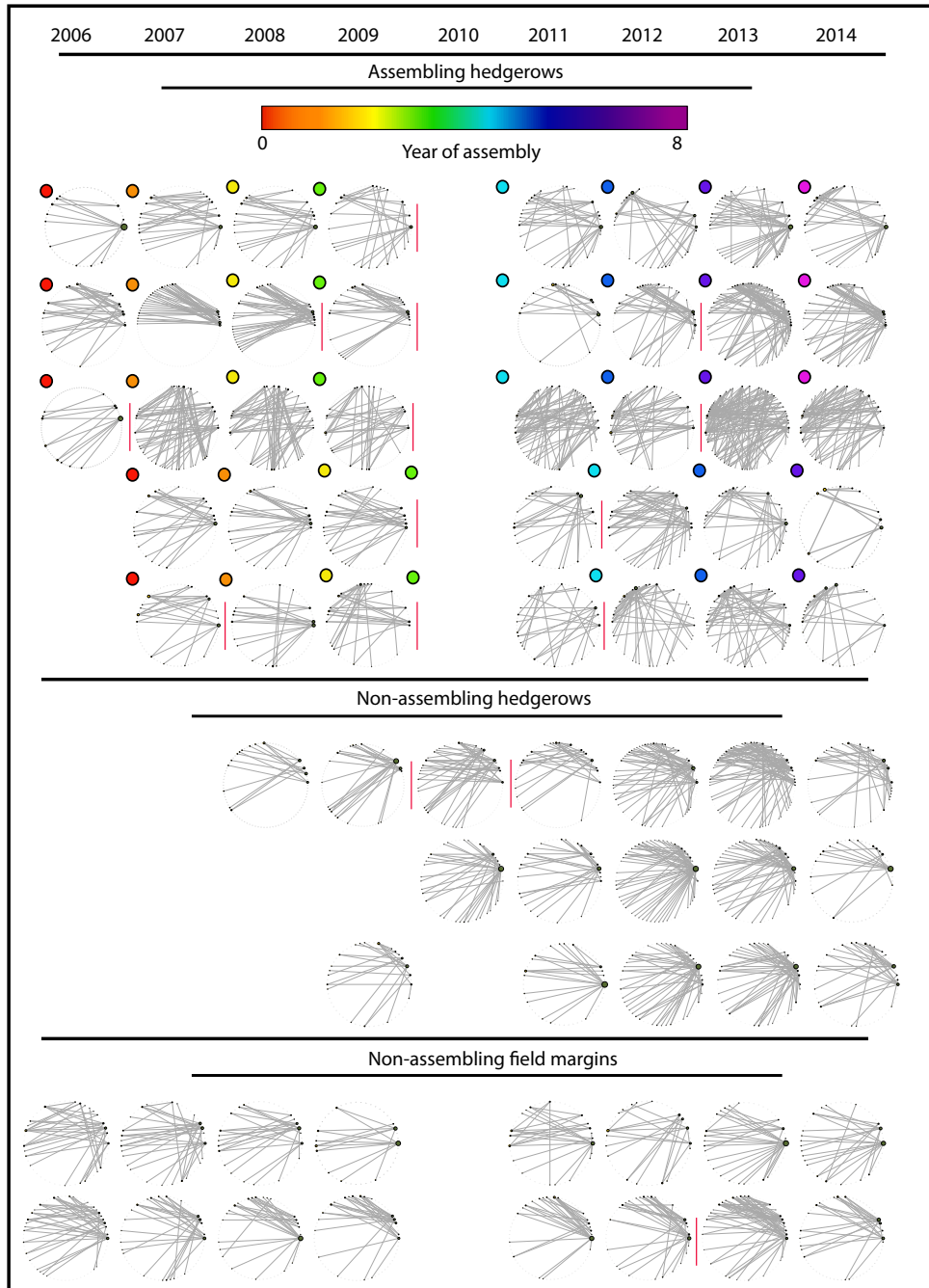


Figure 1: XXX

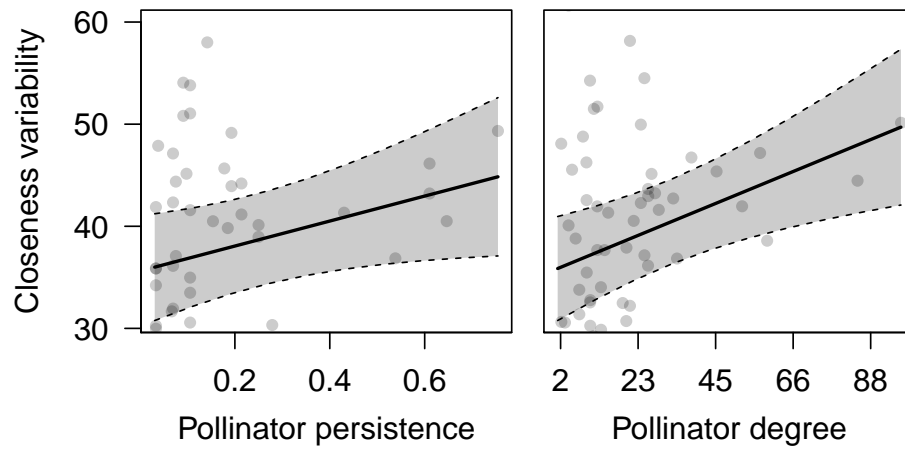


Figure 2: XXX

240 **Characteristics of species that contribute to change points**

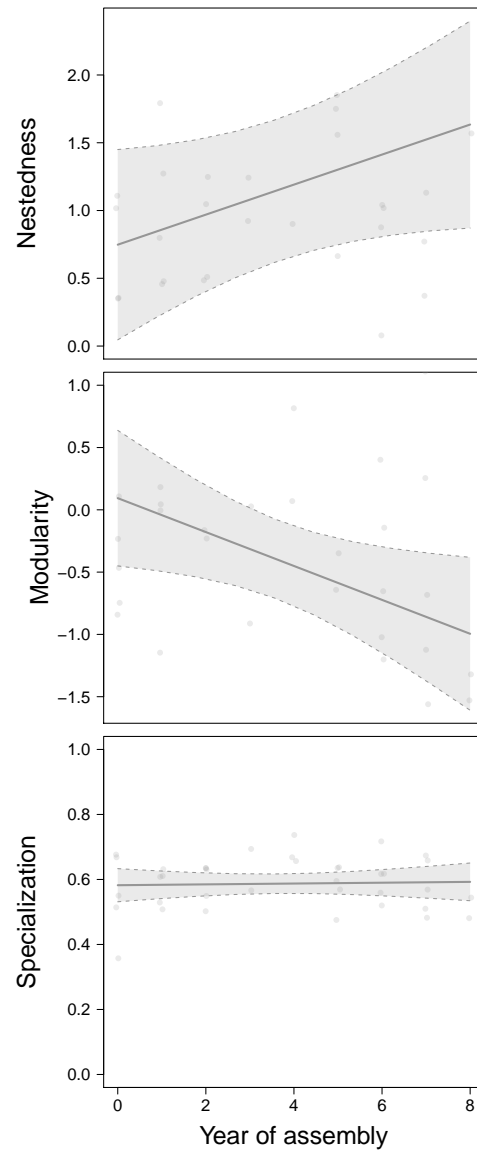


Figure 3: XXX

Network robustness

Discussion

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