

The ecological interpretation of probabilistic networks

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The stochastic nature of ecological interactions has led biologists to adopt a probabilistic view of ecological networks. Representing species interactions probabilistically (how likely they are to occur?) as opposed to deterministically (are they occurring?) allows a better assessment of their spatiotemporal variability and accounts for inherent uncertainties in both observations and predictions. However, despite this growing interest in probabilistic networks, guidelines for the estimation and documentation of probabilistic interaction data are still lacking. This is concerning given that our biological understanding of probabilistic interactions and their appropriate analyses depend on the often elusive methods and variables used for their estimation. We review how probabilistic interactions are defined at different spatial scales, from local interactions to regional networks (metawebs), with a strong emphasis on trophic interactions. These definitions are based on the distinction between the observation of an interaction at a specific time and space and its biological feasibility. We show that different network representations have different statistical properties when it comes to common ecological applications. Specifically, we argue that probabilistic local and metawebs differ in their spatial and temporal scaling of interactions, with potential interactions in metawebs remaining constant across spatial and temporal scales. This is in contrast with the taxonomic scaling of interactions, which does not qualitatively differ between both types of networks. We suggest two approaches to inferring deterministic networks from probabilistic webs that account for these differences and argue that systematic biases arise when directly inferring local webs from subsets of metawebs. To support our arguments, we develop different case studies using open empirical data on host-parasite interactions in Europe. Overall, our results underscore the importance of clear metadata for

probabilistic ecological networks, both at the local and regional scales, to inform the appropriate reuse of interaction data.

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1 Introduction

2 As we try to navigate global biodiversity change, filling in knowledge gaps about biodiversity becomes
3 instrumental to monitoring and mitigating those changes (Gonzalez & Londoño (2022), Abrego *et al.* (2021)).
4 However, cataloging species, populations and, in particular, ecological interactions (e.g., predation, parasitism,
5 and pollination) is a substantial challenge (Polis (1991), Pascual *et al.* (2006)). There are methodological and
6 biological constraints that hinder our ability to observe all ecological interactions, leading to significant
7 uncertainties in our understanding of these interactions. For example, the spatial and temporal uncoupling of
8 species (Jordano (1987)) and the large number of rare and cryptic interactions in a community contribute to
9 these uncertainties (Jordano (2016)). More generally, a handful of conditions must be satisfied for an interaction
10 to be observed locally. First, both species must have overlapping geographic ranges, i.e. they must co-occur
11 within the region of interest (Blanchet *et al.* (2020)). Second, they must have some probability of meeting.
12 Probabilities of interspecific encounters are typically low, especially for rare species with low relative
13 abundances (Canard *et al.* (2012)). The probability that species meet each other also depends on their
14 biological characteristics, such as the synchronization of their phenology (Olesen *et al.* (2010), Singer &
15 McBride (2012)) and their discoverability (e.g., Broom & Ruxton (2005)). Finally, when species do come into
16 contact, an interaction occurs only if their traits are locally compatible
17 (Poisot *et al.* (2015)), including but not limited to their body phenotypes (Bolnick *et al.* (2011), Stouffer *et al.*
18 (2011), Gravel *et al.* (2013)) and behavioral choices (Pulliam (1974), Choh *et al.* (2012)). Interactions may also
19 be influenced by the presence or prevalence of a third species (e.g., of a more profitable prey species) (Golubski
20 & Abrams (2011), Sanders & van Veen (2012)). Documenting the location and timing of interactions becomes
21 even more difficult when accounting for the spatiotemporal variability of ecological interactions (Poisot *et al.*
22 (2012), Poisot *et al.* (2015)). Environmental factors, such as temperature (Angilletta *et al.* (2004)), drought
23 (Woodward *et al.* (2012)), climate change (Gilman *et al.* (2010), Woodward *et al.* (2010), Araujo *et al.* (2011)),
24 and habitat modifications (Tylianakis *et al.* (2007)), contribute to this spatiotemporal variability of interactions
25 by impacting species abundance and traits. Even after satisfying all these conditions, there remains a possibility
26 that the interaction does not occur locally, either due to the intricate nature of the system or simply by chance. If
27 it does occur, it might still go unnoticed, particularly if it happens infrequently. In this context, it is unsurprising
28 that our knowledge of ecological interactions remains limited (Hortal *et al.* (2015)) despite extensive
29 biodiversity data collection (Schmeller *et al.* (2015)).

30 Knowing the biological capacity of two species to interact directly (via e.g., trophic interactions) is necessary
31 but not sufficient for inferring their interaction at a specific time and space. The recognition of the intrinsic
32 variability of species interactions has led ecologists to expand their representation of ecological networks (also
33 known as ecological webs) to include a probabilistic view of interactions (Poisot *et al.* (2016), Dallas *et al.*
34 (2017), Fu *et al.* (2021)). This different perspective allows us to fill in the Eltonian shortfall (Hortal *et al.*
35 (2015)) by modeling the probability of detecting interactions, which can be an important tool for directing
36 efforts and taking action, especially in places where access and resources for research are scarce. Representing
37 interactions probabilistically enables us to capture the spatiotemporal variability of the aforementioned
38 ecological processes and the uncertainties associated with their measurement. As opposed to binary
39 deterministic webs, in which interactions are regarded as either occurring or not, probabilistic webs, within a
40 Bayesian framework, express our degree of belief (or confidence) regarding the occurrence of interactions.
41 Based on the scale at which they are estimated, probabilistic interactions may reflect our level of confidence in
42 whether interactions will be observed, realized, or biologically feasible. As an illustration, we could outline a
43 situation in which there is a 50% certainty that an interaction occurs 50% of the time, or that there is a 50%
44 certainty that it simply occurs. Our level of confidence should be more definitive (approaching either 0 or 1) as
45 we extend our sampling to a broader area and over a longer time period, thereby diminishing the uncertainty of
46 the interactions (but not necessarily the estimation of their variability). In the broadest sense, binary networks
47 are also a type of probabilistic network, in which the numerical value of an interaction is restrained to 0
48 (non-occurring) or 1 (occurring). Yet, for the sake of clarity, we omit binary networks from our discussion of
49 probabilistic networks in this contribution. In probabilistic webs, only forbidden interactions (i.e., interactions
50 prohibited by biological traits or species absence, Jordano *et al.* (2003), Olesen *et al.* (2010)) have a probability
51 value of zero by default, provided that intraspecific trait variability is considered (Gonzalez-Varo & Traveset
52 (2016)).

53 By accounting for the uncertainty of interactions, probabilistic webs may provide a more realistic portrait of
54 species interactions and network structure (i.e. community-level properties), which are major drivers of the
55 functioning, dynamics, and resilience of ecosystems worldwide (Proulx *et al.* (2005), McCann (2007), McCann
56 (2011), Rooney & McCann (2012)). Moreover, the application and development of computational methods in
57 network ecology, often based on a probabilistic representation of interactions, can alleviate (and guide) the
58 sampling efforts required to document species interactions (Strydom *et al.* (2021)). For example, statistical
59 models can be used to estimate the uncertainty of pairwise interactions (Cirtwill *et al.* (2019)) and the

60 probability of missing (false negatives) and spurious (false positives) interactions (Guimerà & Sales-Pardo
61 (2009)). Considering the high rate of false negatives in species interaction data due to the difficulty of
62 witnessing rare interactions (Catchen *et al.* (2023)), these models could inform the identification of priority
63 sampling locations of ecological webs where data collection would yield the most valuable information, thereby
64 reducing errors. Optimization models for sampling locations have mostly found applications in biological
65 systems that are not networks, such as identifying priority sampling sites for disease hotspots (Andrade-Pacheco
66 *et al.* (2020)), but there is substantial promise in applying them to probabilistic ecological interactions.
67 Statistical models can also be used to generate predictions of ecological webs without prior knowledge of
68 pairwise interactions, for instance using body size (Petchey *et al.* (2008), Gravel *et al.* (2013)), phylogeny
69 (Elmasri *et al.* (2020), Strydom *et al.* (2022)), or a combination of niche and neutral processes (Bartomeus *et*
70 *al.* (2016), Pomeranz *et al.* (2019)) for inference. Topological null models, which generate probabilistic
71 networks by preserving chosen characteristics of the binary adjacency matrix while intentionally omitting
72 others (Bascompte *et al.* (2003), Fortuna & Bascompte (2006)), serve as other examples of common
73 probabilistic network models. Null models can be used to produce underlying distributions of network measures
74 for null hypothesis significance testing. Many measures have been developed to describe the structure (Poisot *et*
75 *al.* (2016)) and diversity (Ohlmann *et al.* (2019), Godsoe *et al.* (2022)) of probabilistic webs. These models and
76 measures support the use of this approach for the study of a wide range of ecological questions, from making
77 better predictions of species distribution (Cazelles *et al.* (2016)) to forecasting the impact of climate change on
78 ecological webs (Gilman *et al.* (2010)).

79 The lack of clear guidelines on the use of probabilistic interaction data is worrisome, both for data producers
80 and re-users who generate and manipulate these numbers. This is concerning because sampling strategies and
81 decisions regarding network construction can affect our understanding of network properties (Brimacombe *et*
82 *al.* (2023)). Besides methodological difficulties that may arise when assessing probabilistic interactions, a
83 precise definition of probabilistic interactions appears to be lacking, making the estimation and use of these data
84 more difficult. We aim to take a step back by outlining different ways in which probabilistic interactions are
85 defined and used in network ecology. We distinguish two broad categories of probabilistic webs that necessitate
86 distinct approaches when applied to key ecological questions: local webs describing probabilities of realized
87 interactions, and regional webs (metawebs) describing probabilities of potential interactions. We highlight the
88 distinctions in the ecological meaning of these two representations and show that they yield different statistical
89 outcomes regarding e.g. the spatial and temporal scaling of interactions and the prediction of binary webs

90 across space. Moreover, there is currently no metadata standard that could guide the documentation of all types
91 of probabilistic interactions (although see e.g., Salim *et al.* (2022) who discuss data standards for deterministic
92 mutualistic webs). Well-defined metadata for probabilistic webs would support more adequate manipulation
93 and integration of interaction data from different sources and guard against possible misinterpretations arising
94 from ambiguous definitions of probabilistic networks. These metadata should outline the nature (i.e., local or
95 regional) and type (e.g., predatory or pollination) of the interactions, provide information regarding the
96 taxonomic level, identities, and characteristics (e.g., life stages) of the individuals involved in an interaction,
97 present the mathematical formulation of probabilities, including clearly identified conditional variables (e.g.,
98 spatial and temporal scales), and describe the methods and contexts (e.g., location, time, environmental
99 conditions) in which interactions were estimated. Inadequately documented probabilistic interaction data should
100 be used with caution when analyzing ecological webs. Our observations and advice can be applied to many
101 types of ecological networks, from food webs to host-virus networks. Indeed, excluding networks of indirect
102 interactions such as competition and facilitation networks (Kéfi *et al.* (2015), Kéfi *et al.* (2016)), most
103 ecological webs describe probabilities of direct interactions, which are conceptually and mathematically
104 analogous regardless of their biological type (e.g., trophic and parasitic interactions).

105 **Probabilistic representations of interactions**

106 One of the first aspects to take into consideration when estimating or interpreting probabilities of interactions is
107 knowing if they describe potential or realized interactions. A potential (regional) interaction is defined as the
108 biological capacity of two taxa to interact (i.e., the probability that they *can* theoretically interact) whereas a
109 realized (local) interaction is the materialization or observation of this interaction in a well-defined space and
110 time (i.e., the probability that they interact locally). Here, we use the terms *metaweb* (Dunne (2006)) to
111 designate regional webs of potential interactions and *local webs* (Poisot *et al.* (2012)) for those of realized
112 interactions. Metawebs are the network analogs of the species pool, where local webs originate from a subset of
113 both species (nodes) and interactions (edges) of the regional metaweb (Saravia *et al.* (2022)). Without clear
114 documentation, it can be challenging to know if published probabilistic webs describe local or regional
115 interactions (tbl. 1 provides examples of studies employing both types of probabilistic networks), or if so-called
116 probabilities are in reality *interaction scores* (i.e., non-probabilistic quantitative interactions). When
117 probabilistic regional interactions are used and interpreted as local interactions (and conversely), this may

118 generate misleading findings during data analysis. We believe that a better understanding of the differences,
119 similarities, and relationships between these two probabilistic representations of ecological webs would
120 alleviate interpretation errors and facilitate a more adequate utilization of interaction data.

121 **Pairwise interactions: the building blocks of ecological networks**

122 Local and metawebs, like any type of network, are made of nodes and edges that can be represented at different
123 levels of organization and precision. The basic unit of food webs and other ecological networks are individuals
124 that interact with each other (e.g., by predation, Elton (2001)), forming individual-based networks (Melián *et al.*
125 (2011)). The aggregation of these individuals into more or less homogeneous groups (e.g., populations, species,
126 families) allows us to represent nodes at broader taxonomic scales, which affects our interpretation of the
127 properties of these systems (Guimarães (2020), Hemprich-Bennett *et al.* (2021)).

128 Edges linking nodes can describe a variety of interaction measures. Ecologists have traditionally represented
129 interactions as binary objects that were considered realized after observing at least one individual from group i
130 interact with at least another individual from group j . In a binary adjacency matrix B , the presence or absence
131 of an interaction $B_{i \rightarrow j}$ between two taxa can be viewed as the result of a Bernoulli process

132 $B_{i \rightarrow j} \sim \text{Bernoulli}(P(B_{i \rightarrow j}))$, with $P(B_{i \rightarrow j})$ being the probability of interaction that characterizes our limited
133 knowledge of the system and its intrinsic spatiotemporal variability. In probabilistic networks, $P(B_{i \rightarrow j})$ are edge
134 values, and the only two possible outcomes are the presence ($B_{i \rightarrow j} = 1$) or absence ($B_{i \rightarrow j} = 0$) of an interaction
135 between each pair of nodes. Depending on the type of probabilistic network (local or metaweb), the
136 mathematical formulation and interpretation of stochastic parameters like $P(B_{i \rightarrow j})$ can be linked to
137 environmental and biological factors such as species relative abundance, traits, area, and time (tbl. 1), for
138 example using logistic regression with a logit link function with continuous explanatory variables. Predicting
139 the number of local webs in which the interaction occurs can be achieved by using a Binomial distribution,
140 assuming a constant probability of interaction and independence between networks (trials). When considering
141 uncertainties around the estimation of $P(B_{i \rightarrow j})$, a Beta distribution can also be used to encompass all possible
142 probability values. In that case, a Beta-Binomial distribution can be used to predict the number of networks in
143 which the interaction occurs. Observing an interaction between two taxa at a given location and time provides
144 important information that can be used to update previous estimates of $P(B_{i \rightarrow j})$, informing us on the biological
145 capacity of both taxa to interact and the environmental conditions that enabled them to interact locally.

146 Even though binary webs constitute a highly valuable source of ecological information (Pascual *et al.* (2006)),
147 they overlook important factors regarding interaction strengths. Represented in a quantitative adjacency matrix
148 W as numbers not confined to the $[0, 1]$ range, interaction strengths better describe the energy flows,
149 demographic impacts or frequencies of interactions between nodes (Berlow *et al.* (2004), Borrett & Scharler
150 (2019)), with $W_{i \rightarrow j}$ being a natural \mathbb{N} or real \mathbb{R} number depending on the measure. For example, they may
151 represent local interaction rates between pairs of taxa (e.g., the flower-visiting rates of pollinators in a
152 mutualistic network, Herrera (1989)). When interaction strengths characterize predation pressure on prey taxa
153 in food webs, they can serve as good estimators of the parameters describing species interactions in a
154 Lotka-Volterra model (e.g., Emmerson & Raffaelli (2004)). The extra amount of ecological information in
155 quantitative networks typically comes at a cost of greater sampling effort and data volume in predictive models
156 (Strydom *et al.* (2021)), which can lead to relatively high levels of uncertainties when inferring quantitative
157 webs with limited data.

158 Just like binary networks, the uncertainty and spatiotemporal variability of interaction strengths can be
159 represented probabilistically. However, the need to estimate the probability distribution of all possible values of
160 interaction strengths can make the inference of probabilities more challenging in quantitative webs compared to
161 binary webs, which require only one probability estimate for each interaction. Interaction strengths can follow
162 various probability distributions depending on the measure used. For instance, they can follow a Poisson
163 distribution $W_{i \rightarrow j} \sim \text{Poisson}(\lambda_{i \rightarrow j})$ when predicting frequencies of interactions between pairs of nodes, with
164 $\lambda_{i \rightarrow j}$ being the expected rate at which individuals of taxa i and j interact (e.g., the average number of prey j
165 consumed by all predators i in a given time period). The Poisson distribution can also be 0-inflated after
166 initially modeling non-interacting taxa (e.g., Boulangeat *et al.* (2012) employ a 0-inflated model to analyze
167 species abundance following the modeling of species presence and absence), which constitute the majority of
168 taxa pairs in most local webs due to their typically high sparseness (Jordano (2016)). Because of the
169 methodological difficulties typically encountered when building deterministic quantitative webs (which are only
170 partially mitigated by models such as Ecopath, Plagányi & Butterworth (2004)), binary webs, which are easier
171 to sample (Jordano (2016)) and predict (Strydom *et al.* (2021)), have been more frequently studied and
172 modeled. Moreover, most published probabilistic networks and methods describe probabilistic interactions
173 whose outcome is binary (whether interaction probabilities are regarded as constant or variable, e.g. represented
174 by a Beta distribution), which underlines the need for better guidelines regarding the interpretation and
175 manipulation of these types of webs first. For these reasons, our primary focus in this contribution will be on

176 addressing the challenges in interpreting and using interaction probabilities in Bernoulli distributions, in both
177 probabilistic local and metawebs.

178 **Local webs: communities interacting in space and time**

179 Probabilistic local webs describe how likely taxa are to interact at a given location and time period (i.e.,
180 interactions are contingent upon the environmental and biological conditions of the community). In local webs,
181 edges commonly represent our degree of belief that two taxa interact in nature, but can also represent the
182 probability of *observing* this interaction (Catchen *et al.* (2023)). For example, Gravel *et al.* (2019) used a
183 dataset of binary local European food webs of willow-galling sawflies and their natural enemies, all referenced
184 in space and time and consisting of similar species, to infer the probabilities of locally observing interactions
185 between co-occurring species. This was achieved by situating local webs within the context of environmental
186 variables, i.e. by including temperature and precipitation as conditional variables in some of their models.

187 We define space as the collection of geographic coordinates (x, y, z) , with (x, y) representing longitude and
188 latitude coordinates, and z denoting either altitudes or depths. These point coordinates delineate the spatial
189 boundaries of the system, which may be portrayed as a polyhedron. Ecological interactions may exhibit
190 variations along altitudinal gradients, as evidenced by changes in hummingbird-plant interactions (Weinstein &
191 Graham (2017b) and Weinstein & Graham (2017a)) and mosquito biting rates (e.g., Kulkarni *et al.* (2006)) at
192 different elevations. In contrast, time is defined as the specific time period within which interactions were either
193 observed or predicted. With these definitions in mind, space and time can be conceptualized as distinct patches
194 or time segments. Treating them as discrete dimensions aligns with the common sampling methods of
195 ecological webs and provides actual probabilities of interactions across space and time. This differs from the
196 approach of treating them as continuous variables, where edge values represent probability densities (i.e.,
197 relative likelihoods of interactions occurring at infinitesimal locations and instants in time) rather than discrete
198 probability values (which can be obtained by integrating probability densities). By employing discrete locations
199 and time periods, we can quantify an area (or volume) A and a duration t , which can be readily used in
200 spatiotemporal analyses of ecological networks. For example, when studying network-area relationships (NAR,
201 Galiana *et al.* (2018)), we anticipate that local probabilities of interactions scale positively with area and
202 duration because taxa have more opportunities to interact as these dimensions expand.

203 The probability that two taxa i and j interact in a local web $L_{x,y,z,t}$ (spatial and temporal subscripts hereafter

204 omitted for clarity) can be conditional on many environmental and biological factors. One of these is their
 205 co-occurrence $C_{i,j}$, which is usually a Boolean describing if the geographic distributions of both taxa overlap
 206 within the study area. Co-occurrence can be modeled probabilistically, in which case it may conform to a
 207 Bernoulli distribution $C_{i,j} \sim \text{Bernoulli}(P(C_{i,j}))$, where the probability of co-occurrence $P(C_{i,j})$ can be
 208 estimated through the application of joint species distribution models (e.g., Pollock *et al.* (2014)). Considering
 209 that the probability that two non-co-occurring taxa interact locally is zero (i.e., $P(L_{i \rightarrow j}|C_{i,j} = 0) = 0$), the
 210 probability of local interaction can be obtained by multiplying the probability of interaction given
 211 co-occurrence with the probability of co-occurrence:

$$P(L_{i \rightarrow j}) = P(L_{i \rightarrow j}|C_{i,j} = 1) \times P(C_{i,j} = 1). \quad (1)$$

212 Other important factors that can impact interaction probabilities at the local scale are taxa relative abundance
 213 (Canard *et al.* (2012)) and traits (Poisot *et al.* (2015)), as well as environmental factors such as temperature
 214 (Angilletta *et al.* (2004)), precipitation (Woodward *et al.* (2012)), habitat structure (Klecka & Boukal (2014)),
 215 and presence of other interacting taxa in the network (Pilosof *et al.* (2017), Kéfi *et al.* (2012)), as described
 216 above. Here, we use the variable $\Omega_{x,y,z,t}$ (hereafter simply Ω) to describe the biological and ecological context
 217 in which interaction probabilities were estimated. For example, if a research team conducts a mesocosm
 218 experiment to estimate interaction probabilities between predators and prey with and without shelters (a place
 219 that offers refuge and protection for prey, shielding them from predators), Ω would represent the presence or
 220 absence of these shelters. Like co-occurrence, Ω can also be modeled probabilistically when the stochasticity or
 221 uncertainty of environmental and biological factors is considered. In sum, Ω represents all ecological and
 222 biological variables that were taken into consideration when measuring interaction probabilities and is,
 223 therefore, a subset of all factors actually impacting ecological interactions.

224 The probability that two taxa i and j interact in a local web L can thus be conditional on the area (or volume) A ,
 225 the time interval t , their co-occurrence $C_{i,j}$ and chosen environmental and biological conditions Ω . Although
 226 these variables are associated with distinct questions or mechanisms related to ecological interactions, they may
 227 covary with each other, such as the possible dependence of $C_{i,j}$ and Ω on spatial and temporal scales. When
 228 estimating interaction probabilities using e.g. a generalized linear model with multiple explanatory variables
 229 that might not be independent, it may become important to address collinearity. Using variable selection
 230 techniques, for instance, may be necessary before fitting the model to mitigate this issue. The probability of

231 local interaction is described by the following expression when all these conditional variables are included:

$$P(L_{i \rightarrow j} | A, t, C_{i,j}, \Omega) \quad (2)$$

232 The representation of the local context in which probabilities are estimated and the variables that should be
 233 taken into consideration depend on the study system, the objectives of the study, and the resources available to
 234 the researchers. In other words, these variables do not systematically need to be accounted for. For example, in
 235 Gravel *et al.* (2019), for the purpose of model comparison, some models incorporated environmental variables
 236 as conditional factors to estimate interaction probabilities, while others did not. When accounted for, these
 237 variables should be clearly described in the documentation of the data (Brimacombe *et al.* (2023)),
 238 preferentially in mathematical terms to avoid any confusion in their interpretation and to limit manipulation
 239 errors during their re-use. For instance, ecologists should be explicit about their consideration of co-occurrence
 240 in their estimation of local interaction probabilities. Indeed, it is important to specify if probability values are
 241 conditional $P(L_{i \rightarrow j} | C_{i,j} = 1)$ or not $P(L_{i \rightarrow j})$ on co-occurrence since this can significantly impact the
 242 interpretation and analysis of the data. In [tbl. 1](#), we present examples of studies that used these diverse
 243 formulations of probabilistic interactions and conditional variables.

Table 1: Mathematical expression of probabilistic interactions. The probability of interaction between two taxa i and j is interpreted differently in a metaweb M of potential interactions and a local web L of realized interactions. Each expression includes a different conditional variable, when applicable. An example of a study employing each of these notations and conditional variables is provided, with the specific variables used indicated in parentheses. The study marked with an asterisk has been carried out on binary webs. Note that interaction probabilities can be contingent upon multiple conditional variables, or none at all. Additionally, local interaction probabilities might represent the probability of observing an interaction, not necessarily its actual occurrence.

Expression	Type	Outcome	Reference
$P(M_{i \rightarrow j})$	regional	biological feasibility of the interaction	Strydom <i>et al.</i> (2022)
$P(L_{i \rightarrow j})$	local	realization of the interaction	Fortuna & Bascompte (2006) (null model)
$P(L_{i \rightarrow j} A)$	local	realization of the interaction in a given area or volume	Galiana <i>et al.</i> (2018) *
$P(L_{i \rightarrow j} t)$	local	realization of the interaction during a given time period	Weinstein & Graham (2017a)

Expression	Type	Outcome	Reference
$P(L_{i \rightarrow j} C_{i,j})$	local	realization of the interaction given that the taxa co-occur	Gravel <i>et al.</i> (2019)
$P(L_{i \rightarrow j} \Omega)$	local	realization of the interaction given environmental conditions	Gravel <i>et al.</i> (2019) (temperature and precipitation)
$P(L_{i \rightarrow j} M_{i \rightarrow j})$	local	realization of the interaction given that the taxa can biologically interact	this study

244 Metawebs: regional catalogs of interactions

245 Metawebs are networks of potential interactions that have been designed for broad spatial, temporal, and
 246 taxonomic scales (e.g., species food webs at the continental scale). They represent the probability that taxa can
 247 biologically interact regardless of their co-occurrence and local environmental conditions. Regional interactions
 248 are by definition context-independent, i.e. they are not measured at a specific location and time. In contrast with
 249 probabilistic local webs, which represent the stochasticity of interactions occurring in nature, probabilistic
 250 metawebs measure our degree of belief in the capacity of two taxa to interact (i.e., the probability that their
 251 traits could support an interaction in the right conditions). Consequently, although *neutrally* forbidden
 252 interactions (i.e., improbable interactions between rare species, Canard *et al.* (2012)) tend to have low
 253 probability values in local webs, they may exhibit a higher probability in the metaweb. Potential interactions
 254 describe the probability that there exists at least one combination of phenotypes of taxa i and j that can interact
 255 with each other if they were to encounter. To reduce any biases in our calculation of this probability, it is crucial
 256 to ensure that the set of traits sampled or considered accurately reflects the overall trait distribution in both taxa.
 257 This enhances our confidence in concluding that the taxa cannot interact when no positive observation has been
 258 made and increases our capacity to detect an interaction when it is biologically feasible. In addition to pairwise
 259 interactions, the extent of sampling effort also contributes to shaping our assessment of metaweb properties, as
 260 sampling a larger number of local webs allows us to capture more regional interactions (McLeod *et al.* (2021)).
 261 A probability of potential interaction in a metaweb M can be expressed as

$$P(M_{i \rightarrow j}), \quad (3)$$

which, in contrast with local webs, is never conditional on any spatial, temporal, co-occurrence or environmental variables (tbl. 1).

Starting from a selected set of taxa, which are usually distributed within a broad region of interest, probabilistic metawebs can be built using different data sources, including literature review, fieldwork, and predictive models (e.g., the metaweb of trophic interactions between Canadian mammals inferred by Strydom *et al.* (2022)). Every pair of taxa that have confidently been observed to interact at least once can be given a probability of 1 (i.e., $P(M_{i \rightarrow j}) = 1$) since we know that they *can* interact. This is not the case in local probabilistic webs, in which interaction events usually remain stochastic (i.e., $P(L_{i \rightarrow j}) < 1$) after empirically observing interactions because of their intrinsic spatiotemporal variability. Similarly, although rare interactions typically have low probabilities in local webs, they can have high probabilities in metawebs when the traits of both taxa are congruent. On the other hand, interactions that were never observed can have low probability values in both local and metawebs, going as low as 0 for forbidden links. However, because of observation errors due to taxonomic misidentifications and ecological misinterpretations (e.g., due to cryptic species and interactions, Pringle & Hutchinson (2020)), many observations of interactions are in reality false positives. Likewise, forbidden interactions can be false negatives in metawebs, e.g. if they have been assessed for specific phenotypes, locations or time. Employing Bayesian models, whether they are mechanistic or phenomenological, could improve the accuracy of our estimation of interaction probabilities within both local and regional webs (e.g., Bartomeus *et al.* (2016), Cirtwill *et al.* (2019)). This improvement is achieved in metawebs by leveraging prior information regarding the feasibility of interactions along with the empirical data on observed interactions.

Properties of probabilistic webs

Probabilistic local and metawebs differ in their type of interactions (i.e., realized or potential) and in the conditional variables upon which interaction values depend. These differences are significant as they influence the characteristics of probabilistic networks. Neglecting to consider them may result in misleading results and interpretation errors when analyzing the properties of probabilistic webs, which could be particularly problematic when addressing crucial ecological questions about networks. Here we compare the characteristics of local and metawebs through the presentation of four common applications of probabilistic interactions. All code and data to reproduce these analyses are available at the Open Science Framework (TBD).

289 **Host-parasite network data**

290 We use the collection of tripartite host-parasite networks sampled across Europe, created by Kopelke *et al.*
291 (2017), in most of our case studies. This dataset contains well-resolved binary local interactions between
292 willows (52 species), willow-galling sawflies (96 species), and their parasitoids (126 species). Given its
293 replicated webs spanning large spatiotemporal scales, this dataset is well-suited for analyzing a variety of
294 ecological hypotheses and processes. Out of a total of 374 local webs, we retained those containing at least 5
295 species, resulting in a set of 233 georeferenced local webs (networks sampled within areas of 0.1 to 0.3 km²
296 during June and/or July spanning 29 years). We built a binary metaweb by aggregating all local interactions,
297 which gave us a regional web composed of 274 species and 1080 interactions. In the first two panels of fig. 1,
298 we show how the dissimilarity of interactions between common species (β_{OS}) and the dissimilarity in species
299 composition (β_S) between the metaweb and aggregated local webs (Poisot *et al.* (2012)) vary with the number
300 of sampled local webs. This shows that networks of local interactions are highly dissimilar from the metaweb,
301 both in terms of species and interactions, especially when only a limited number of sites has been sampled.
302 Both dissimilarity indices were calculated based on the number of items shared by the two webs (c_{LM}) and the
303 number of items unique to the metaweb (u_M) and to the aggregated local web (u_L). The β_S dissimilarity index
304 uses species (nodes) as items being compared, while the β_{OS} index assesses dissimilarity based on interactions
305 between shared species (Poisot *et al.* (2012)). Both indices were calculated following the β_W index of
306 Whittaker (1960):

$$\beta_W = \frac{c_{LM} + u_L + u_M}{(2c_{LM} + u_L + u_M)/2} - 1. \quad (4)$$

307 [Figure 1 about here.]

308 We converted these binary networks into probabilistic ones using models based on simple assumptions. Our
309 models are not designed to estimate the exact values of probabilistic interactions. Instead, their purpose is to
310 create plausible networks that serve as illustrative examples to highlight distinctions between probabilistic local
311 and metawebs. We created two probabilistic metawebs by employing constant false positive and false negative
312 rates for all regional interactions. In the first metaweb, we set both false positive and false negative rates to zero
313 to prevent artificially inflating the total number of links, enabling a more accurate comparison with binary webs.
314 This gave us a probability of regional interaction of 1 when at least one interaction has been observed and of 0

315 in the absence of any observed interaction between a given pair of species. In the second metaweb, we
 316 introduced a 5% false positive rate to account for spurious interactions and a 10% false negative rate to address
 317 the elevated occurrence of missing interactions in ecological networks (Catchen *et al.* (2023)). We believe these
 318 rates represent reasonable estimates of missing and spurious potential interactions, but confirming their
 319 accuracy is challenging due to the unavailability of data on the actual feasibility of interaction. Observed
 320 interactions were thus given a probability of regional interaction of 95%, whereas unobserved ones were
 321 assigned a probability of 10%.

322 To build probabilistic local webs, we first recognize that local interactions must initially be biologically feasible
 323 before occurring at a specific time and space. A local probability of interaction $P(L_{i \rightarrow j})$ can be expressed as the
 324 product of the probability of local interaction given that the two taxa can potentially interact $P(L_{i \rightarrow j}|M_{i \rightarrow j} = 1)$,
 325 which we denote as $P(L|M)$ for the sake of simplicity, with their probability of regional interaction $P(M_{i \rightarrow j})$:

$$P(L_{i \rightarrow j}) = P(L_{i \rightarrow j}|M_{i \rightarrow j} = 1) \times P(M_{i \rightarrow j} = 1). \quad (5)$$

326 We built the probabilistic local webs from the binary ones by using the probabilistic metawebs and a constant
 327 value of $P(L|M)$ across interactions. Low values of $P(L|M)$ indicate that feasible interactions rarely occur
 328 locally, intermediate values around 50% suggest considerable spatiotemporal variability, while high values
 329 indicate that regional interactions are nearly always realized locally. Following eq. 5, the local probability of
 330 interaction between a given pair of taxa consistently remained equal to or below their probability of regional
 331 interaction.

332 In the last two panels of fig. 1, we show how the aggregated number of links and connectance (i.e., the
 333 proportion of all of the non-forbidden links that are realized) scale with the number of sampled local
 334 probabilistic webs, according to different values of $P(L|M)$. When aggregating local probabilistic webs, the
 335 constancy of the probability of regional interaction across the entire study area means that any rise in the
 336 probability of local interaction is solely attributable to an increase in $P(L|M)$. The probability $P(L_{1,2}|M)$ of
 337 local interaction among potentially interacting species in an aggregated web $L_{1,2}$ is obtained by:

$$P(L_{1,2}|M) = 1 - (1 - P(L_1|M)) \times (1 - P(L_2|M)), \quad (6)$$

338 where $P(L_1|M)$ and $P(L_2|M)$ are the probabilities of local interaction among two potentially interacting species

339 in the subnetworks L_1 and L_2 , respectively. This equation provides the probability that the interaction is realized
340 in either (1) exclusively the local web L_1 , (2) exclusively the local web L_2 or (3) both local webs, given that the
341 two taxa have the biological capacity to interact.

342 By comparing the scaling relationships observed in binary and probabilistic webs, fig. 1 illustrates that high
343 values of $P(L|M)$ lead to systematic overestimations in the number of links and connectance, especially when
344 $P(L|M) = 1$ (corresponding to the scenario where local probabilities of interactions are equivalent to the
345 probabilities of regional interactions). However, these biases tend to diminish as the number of sampled webs
346 increases.

347 Taxonomic scaling of interactions

348 Probabilistic webs offer a versatile approach to tackle a broad array of ecological questions, depending on their
349 level of organization. For instance, the assemblage of interactions across ecological scales can be explored
350 through species-based networks, while clade-based networks provide insights into macroevolutionary processes
351 (e.g., Gomez *et al.* (2010)). Given that our interpretation of the properties and dynamics of ecological webs
352 depends on their taxonomic scale (Guimarães (2020)), investigating the phylogenetic scaling of network
353 structure emerges as a promising research avenue. Examining the same system at various taxonomic scales can
354 yield meaningful and complementary ecological information, and, in our perspective, employing probabilistic
355 webs is an effective approach for such analyses.

356 There are no inherent differences in the taxonomic scaling between local and metawebs, as only the nodes are
357 defined taxonomically. In other words, the probability values of edges in both local (eq. 2) and metawebs (eq. 3)
358 are not conditional on any taxonomic scale. The phylogenetic scale is tied to the definition of the event itself
359 (i.e., the interaction between two taxa), not to the conditional variables. In both types of webs, transitioning to a
360 broader level of organization (e.g., from a species-level web S to a genus-level web G) can be accomplished
361 directly by using probabilities from finer scales. For example, in a network with n_1 species from genus g_1 and
362 n_2 species from genus g_2 , one can compute the probability that at least one species from genus g_1 interacts with
363 at least one species from genus g_2 as follows:

$$P(G_{g_1 \rightarrow g_2}) = 1 - \prod_{i=1}^{n_1} \prod_{j=1}^{n_2} (1 - P(S_{g_1 i \rightarrow g_2 j})), \quad (7)$$

364 where $g_1 i$ and $g_2 j$ are the species of the corresponding genus. If it is known that at least two of these species

365 interact (i.e., $P(S_{g_{1i} \rightarrow g_{2j}}) = 1$ for at least one pair of (g_{1i}, g_{2j})), it implies a probability of genus interaction
366 equal to 1. Canard *et al.* (2012) built a species-based network following a similar approach, by using simulated
367 interactions between individuals derived from a neutral model (i.e., a model that assumed ecological
368 equivalence among individuals). In contrast, a more sophisticated approach is necessary when transitioning
369 from a broader to a finer level of organization. This is because knowledge of an interaction between two genera
370 does not guarantee that all possible pairwise combinations of their species will also interact. One possible
371 method is to build a finer-scale network by generating probabilities of interactions through random sampling
372 from a beta distribution, parameterized by the broader-scale network.

373 Ideally, our biological interpretation of probabilistic interactions should remain consistent across a network
374 even if it incorporates heterogeneous levels of organization, such as a network whose nodes represent both
375 species and trophic species (groups of species sharing similar predators and prey). This is common in
376 ecological webs where taxonomic resolution is typically low (Hemprich-Bennett *et al.* (2021), Vázquez *et al.*
377 (2022)). Interaction probabilities at broader taxonomic scales should be based on probabilities of interactions
378 between individuals, for both local and metawebs. For instance, in local individual-based food webs, the
379 probability that two individuals interact reflects our degree of belief that one individual will consume the other.
380 Similarly, in local species-based food webs, the probability that two species interact represents our degree of
381 belief that at least one individual from the predator species consumes at least another individual from the prey
382 species. Furthermore, in local clade-based food webs, the probability that two clades interact represents our
383 degree of belief that at least two species from these clades interact with each other or, equivalently, that at least
384 two individuals from these clades interact with each other. Fundamentally, the taxonomic scaling of interactions
385 involves aggregating interactions between individuals into larger groups, which may exhibit varying degrees of
386 homogeneity based on the organisms and the study system. In that regard, taxonomic scaling is analogous to the
387 spatial and temporal scaling of interactions, as they all represent different ways to aggregate individuals into
388 broader groups (either spatially, temporally, or taxonomically).

389 **Spatial and temporal scaling of interactions**

390 The investigation of network-area relationships and interaction accumulation curves is an important area of
391 research in network ecology. First, network-area relationships elucidate the scaling of network properties (such
392 as modularity and trophic chain lengths) with spatial scale (e.g., Wood *et al.* (2015), Galiana *et al.* (2018)). The
393 variations in network structure across spatial scales may stem from the scaling of species richness (species-area

relationships, SARs) and the number of interactions (Brose *et al.* (2004)) with the sampled area. Additionally, ecological processes unfolding at distinct spatial scales, such as the spatial variability in local community composition resulting from different sequences of extinction and colonization events, can also contribute to this variation (Galiana *et al.* (2018)). Next, interaction accumulation curves describe the scaling of the number of observed interactions with sampling effort (Jordano (2016)). Sampling effort, which may correspond to the duration of the sampling period used to construct the network, can impact connectance (Bersier *et al.* (1999)) and various measures of network structure (Banašek-Richter *et al.* (2004), McLeod *et al.* (2021)). Apart from sampling effort, the temporal scaling of interactions also elucidates how network structure changes with the temporal resolution of the network (Poisot *et al.* (2012)), acknowledging that distinct interactions take place over time, ranging from short-term fluctuations of interactions to long-term trends. As probabilistic local webs may explicitly account for the spatiotemporal variability of interactions, they offer a distinct approach to investigating the scaling of network structure with space and time, in contrast to binary and quantitative webs, by making the stochasticity of interactions the focal point of the modeling process.

Local and metawebs exhibit distinct relationships with spatial and temporal scales. On one hand, probabilistic metawebs, being independent of any local context, feature regional interactions that do not scale with space and time. This is because regional interactions depend solely on the biological capacity of two taxa to interact, regardless of their co-occurrence and specific environmental conditions. However, probabilities of potential interactions may change (tending to become more definitive) upon updating previous estimates with increased sampling effort, even though they do not vary in a specific direction with the spatial and temporal extent (boundaries) of the network. The probability of two taxa potentially interacting should theoretically be the same in all metawebs in which they are present, provided that the data and methods used for estimation are consistent. For example, if a smaller metaweb M_1 is derived from a larger metaweb M_0 by selecting the subset of taxa present in the region described by M_1 and retaining all their interactions, their probabilities of interaction should be identical regardless of scale, i.e. $P(M_{1,i \rightarrow j}) = P(M_{0,i \rightarrow j})$. With a larger or equal number of taxa in M_0 as compared to M_1 , the total number of interactions is expected to be higher or at least equal in the larger web, even though pairwise probabilities remain identical.

On the other hand, local interactions scale both spatially and temporally, given that they have more opportunities to be realized and observed in larger areas and longer durations. This is attributed to factors such as a higher number of individuals, greater trait variations, and increased opportunities for encounters, as highlighted by McLeod *et al.* (2020). For example, if a local probabilistic web L_1 with an area A_1 is derived

424 from a larger web L_0 with an area A_0 , and A_1 is entirely nested within A_0 , interaction probabilities should be
425 lower in the smaller web, i.e. $P(L_{1,i \rightarrow j}|A_1 < A_0) \leq P(L_{0,i \rightarrow j}|A_0)$. However, if A_1 and A_0 are disjoint, interaction
426 probabilities could be higher in the smaller area, contingent upon their environmental and biological conditions.
427 Likewise, interaction probabilities are expected to be lower in webs with shorter durations when time intervals
428 are nested. In fig. 2, we show how the expected number of local host-parasite interactions scales with area,
429 represented as an expanding latitudinal window, in comparison with regional interactions. Even though we
430 employed local probabilities of interactions equal to regional interactions for the purpose of comparison (i.e.,
431 using $P(L|M) = 1$ here), we notice that the total number of regional interactions scales more rapidly than local
432 interactions. This is because numerous regional interactions involve species that never co-occur, and as a result,
433 these interactions are not captured in local webs.

434 [Figure 2 about here.]

435 **Box 1: A spatiotemporally explicit model of interactions**

436 Predicting local webs across time and space is a pivotal goal of network ecology, especially given the scarcity of
437 interaction data (Strydom *et al.* (2021)). Ecologists may resort to predictive models (e.g., generative Bayesian
438 and machine learning models) to reconstruct networks at fine spatial and temporal scales with limited
439 interaction data. For instance, real-time biomonitoring data coupled with appropriate numerical models (Bohan
440 *et al.* (2017)) can be employed to reconstruct local ecological webs, opening avenues for in-depth studies on
441 local ecosystem functioning and dynamics. The probabilistic representation of interactions acknowledges the
442 inherent uncertainty in these models, typically expressed through probability distributions. We introduce and
443 develop a simple generative mechanistic model for probabilistic local interactions that takes into consideration
444 their spatiotemporal variability (i.e. a spatiotemporally explicit model of local interactions). It is essential to
445 note that our model is not designed for regional interactions, which are scale-independent. Rather, it could
446 prove valuable for predicting local interactions across time and space by generating new interaction data
447 following parameter inference.

448 As indicated by eq. 1, the probability that two taxa i and j interact at a specific location (x, y, z) may be
449 determined by the product of their probability of interaction given co-occurrence and their probability of
450 co-occurrence. First, their co-occurrence probability can be calculated using their individual occurrence
451 probabilities $P(X_i)$ and $P(X_j)$, along with the strength of association γ between their occurrences and

452 co-occurrence (Cazelles *et al.* (2016)):

$$P(C_{i,j}) = P(X_i, X_j) = P(X_i)P(X_j)\gamma. \quad (8)$$

453 When $\gamma > 1$, it signifies a positive association in the geographic distributions of both taxa, indicating that the
454 presence of one taxon enhances the probability of occurrence of the other. In empirical webs, $\gamma > 1$ holds true
455 for the majority of species pairs (Catchen *et al.* (2023)). The co-occurrence of both taxa is modeled as the
456 outcome of a Bernoulli trial

$$C_{i,j} \sim \text{Bernoulli}(P(X_i, X_j)). \quad (9)$$

457 Next, the probability of interaction given co-occurrence can be made temporally explicit by modeling it as a
458 Poisson process with rate parameter λ . This parameter represents the expected frequency of interaction between
459 the taxa within a defined time interval and can be estimated using prior data on interaction strengths, when
460 accessible. The probability that two co-occurring taxa engage in an interaction during a time period t_0 is given
461 by:

$$P(L_{i \rightarrow j} | C_{i,j} = 1) = 1 - e^{-\lambda t_0}, \quad (10)$$

462 which tends toward 1 as $t_0 \rightarrow \infty$. It is important to note that the units of λ and t_0 are complementary. For
463 instance, if the duration t_0 is measured in months, λ denote the expected number of interactions per month.
464 The occurrence of an interaction between i and j can be modeled as a Bernoulli trial with a probability of
465 $P(L_{i \rightarrow j})$. Consequently, a Bayesian inference model can be built based on the preceding equations to estimate
466 the value of the λ and γ parameters and generate novel interaction data:

$$L_{i \rightarrow j} \sim \text{Bernoulli}(P(L_{i \rightarrow j})) \quad (11)$$

$$P(L_{i \rightarrow j}) = P(X_i)P(X_j)\gamma(1 - e^{-\lambda t_0}) \quad (12)$$

$$\gamma \sim \text{Gamma}(2, 0.5) \quad (13)$$

$$\lambda \sim \text{Exponential}(2) \quad (14)$$

467 In fig. 3, we show the variation in the probability of interaction under different parameter values. In the right
468 panel, we notice that, irrespective of the interaction rate λ , the probability of interaction converges toward an
469 asymptote determined by the co-occurrence $P(C_{i,j})$ (eq. 8). This model can be customized in different ways,
470 such as by linking λ with specific environmental variables or explicitly incorporating observation errors (i.e.,
471 the probabilities of false negatives and false positives).

472 [Figure 3 about here.]

473 Sampling for binary webs

474 The prediction of binary interactions through Bernoulli trials is an important application of probabilistic webs.
475 This approach proves beneficial for analyzing the structural characteristics of probabilistic webs, particularly in
476 the absence of specific analytical measures. By performing independent Bernoulli trials for each interaction in a
477 probabilistic web, a binary network may be generated. A probability distribution of network properties can be
478 obtained by measuring network structure across multiple randomly generated networks (Poisot *et al.* (2016)).
479 This method enables the representation of the variability of network structure, albeit with possible biases when
480 connectance is low (Poisot & Gravel (2014), Chagnon (2015)). Employing this strategy to generate binary
481 networks under a null model facilitates null hypothesis significance testing, wherein the observed measure is
482 compared against the simulated distribution (e.g., Bascompte *et al.* (2003)). Additionally, the random
483 generation of binary networks, from a probabilistic web that accounts for the spatiotemporal variability of
484 interactions, may effectively capture network structure across space and time. This facilitates the investigation
485 of ecological hypotheses about interactions at broad spatial and temporal scales.
486 There are at least two distinct approaches to sample binary networks from probabilistic webs across space, for
487 example, when attempting to predict a binary network for each of a number of locations within a given region.
488 The first approach involves performing a singular Bernoulli trial for each pair of taxa based on their regional
489 probability of interaction. In employing this approach, every pair of taxa predicted to interact in the binary

490 metaweb will be treated as interacting in all local webs where they co-occur. This will result in local pairwise
491 interactions without spatial variation. The second approach is to independently sample each of the local
492 probabilistic webs, which can be achieved by first generating distinct probabilistic networks for each location.
493 These local probabilistic webs may vary in taxa composition and interaction probabilities. Subsequently, binary
494 networks can be independently sampled for each location, introducing spatial variation in binary interactions.

495 In fig. 4, we compare the average connectance of binary networks resulting from these two sampling techniques,
496 where regional and local interactions are drawn from our host-parasite probabilistic networks, generating a
497 number of binary web realizations for each site in the dataset. These two sampling approaches yield different
498 outcomes, particularly for lower values of $P(L|M)$, which denote instances where regional interactions do not
499 consistently manifest locally. Small discrepancies are also apparent between these techniques when we equate
500 the probability of local interaction to the probability of regional interaction (i.e., when using $P(L|M) = 1.0$ in
501 eq. 5), especially when the number of binary network samples for each location is low. As anticipated, we
502 observe that sampling binary interactions from the metaweb tends to overestimate connectance on average
503 compared to sampling them from local webs. Furthermore, we observe an increase in the variability of
504 connectance when employing a single sample, representing what we consider as a more tangible process
505 leading to the realization of local and regional interactions in nature.

506 [Figure 4 about here.]

507 The choice of a sampling approach can influence the selection of grid cell size when delineating local
508 communities within a broader region of interest. In the first approach, pairwise interactions remain constant
509 irrespective of cell size since they are sampled only once from the metaweb. However, in the second approach,
510 local interaction probabilities are contingent on the network area. For instance, consider the local webs L_1 and
511 L_2 with an area of $\frac{1}{2}A_0$, both nested within A_0 but disjoint from each other, forming L_0 . If we treat L_1 and L_2 as
512 independent, the probability of interaction between taxa i and j in L_0 is given by:

$$P(L_{0,i \rightarrow j}) = 1 - (1 - P(L_{1,i \rightarrow j}) \times P(L_{2,i \rightarrow j})). \quad (15)$$

513 Due to its larger area, the probability that the two taxa interact in L_0 is equal or greater than in L_1 and L_2 . When
514 sampling binary interactions from local webs, it is crucial to sample at the same spatial scale for which
515 probabilities were estimated. Otherwise, interaction probabilities must be adjusted to align with the intended

516 cell size, preventing systematic biases in predictions.

517 Prediction of local webs from metawebs

518 Metawebs serve as a valuable source of ecological information for predicting local webs across time and space.
519 Binary local webs can be reconstructed by selecting a subset of taxa and interactions from the metaweb (Dunne
520 (2006)). This implies that metawebs consistently contain more interactions than their corresponding local webs.
521 Determining the list of taxa to select can be achieved empirically or through methods like range maps or species
522 distribution models. As the species composition of a community is arguably less difficult to sample or predict
523 than its interactions, the primary challenge lies in deciding which interactions to select from the metaweb, a task
524 that may necessitate advanced statistical models and ecological expertise. Inferring the structure of local webs
525 from the metaweb before predicting specific local pairwise interactions could hold promise (Strydom *et al.*
526 (2021)), considering that the structure of local webs is constrained by the metaweb (Saravia *et al.* (2022)).
527 Building probabilistic local webs from a probabilistic metaweb involves a reduction in the value of pairwise
528 interaction probabilities. This decrease is attributed to the prerequisite that two taxa must initially possess the
529 capacity to interact before engaging in local interactions (eq. 5). Therefore, inferring local webs from their
530 metaweb while maintaining identical interaction probability values would introduce systematic biases into the
531 predictions. In such cases, these networks would essentially represent smaller-scale metawebs of potential
532 interactions, possibly leading to misinterpretations by being perceived as local interactions. As proposed by
533 McLeod *et al.* (2021), although metawebs do not capture the spatiotemporal variability of interactions, they
534 establish an upper limit for local interactions. In other words, the probability of two taxa interacting at a specific
535 location and time is consistently lower or equal to the probability of their regional interaction:

$$P(L_{i \rightarrow j} | A, t, C, \Omega) \leq P(M_{i \rightarrow j}). \quad (16)$$

536 Moreover, the probability that two taxa possess the biological capacity to interact must exceed the probability of
537 them interacting at any location and time because they may never co-occur or encounter locally. Specifically,
538 the cumulative probability of local interactions across all spatial, temporal, and environmental conditions must
539 be less than the probability of regional interaction, i.e.

$$\int_{\Omega} \int_A \int_t P(L_{i \rightarrow j} | A, t, \Omega) dt dA d\Omega \leq P(M_{i \rightarrow j}). \quad (17)$$

540 Estimating more precisely the probability $P(L|M)$ that two taxa interact locally if they can potentially interact
541 allows for improved predictions of local webs from a probabilistic metaweb. This task is challenging due to the
542 variability of this probability across space and time, as well as its variability across pairwise interactions within
543 a network. Using simple models of $P(L|M)$, as demonstrated in our case studies, represents an initial step
544 toward the overarching objective of reconstructing local webs from metawebs.

545 Conclusion

546 In this contribution, we underline the importance of network metadata for adequately interpreting and
547 manipulating probabilistic interaction data. The mathematical representation of probabilities and their statistical
548 properties depend on the type of interactions (local or regional) and the conditions under which these
549 interactions were evaluated. We showed that probabilistic local and metawebs differ in their relationship to
550 spatial and temporal scales, with regional interactions remaining consistent across scales. In contrast with
551 metawebs, local interactions are measured in a specific context (e.g., in a given area, time, and biological and
552 environmental conditions) and depend on taxa co-occurrence. These important conceptual differences bring to
553 light the need to use probabilistic data with caution, for instance when generating binary network realizations
554 across space and predicting local webs from metawebs. Clear metadata describing the type of interaction and
555 the variables used in their estimation are required to ensure adequate data manipulation. Better data practices
556 and foundations for probabilistic thinking in network ecology could enable more reliable assessments of the
557 spatiotemporal variability and uncertainty of biotic interactions.

558 It is essential to enhance our comprehension of both regional and local interactions, especially considering the
559 current scarcity of interaction data. However, while sampling biological communities does decrease the
560 uncertainty of interactions by accumulating evidence for their feasibility and local realization, there is a limit to
561 how much we can diminish their inherent randomness. In metawebs, probabilities reflect our limited knowledge
562 of interactions (i.e., our degree of belief that interactions are feasible), which is expected to improve with a
563 larger volume of data. We should anticipate that regional interactions will become more definitive (with
564 probabilities approaching 0 or 1) as we investigate various conditions, including different combinations of
565 species traits. Conversely, in the case of local webs, which can be seen as random instances of metawebs,
566 randomness cannot be as reduced. In local interactions, probabilities can be divided into a component
567 representing uncertainty and another representing spatiotemporal variability. Owing to environmental

568 heterogeneity, there will invariably be instances in which an interaction occurs and others in which it does not,
569 across different times and locations, irrespective of the extent to which we can improve our knowledge of its
570 biological feasibility and the local conditions that facilitate its occurrence. When local webs depict probabilities
571 of observing interactions rather than just their actual occurrence, we must also consider the observation
572 variability as an additional source of randomness. Every ecological process is stochastic but there is also a
573 possibility that a phenomenon goes undetected. Quantifying and partitioning this stochasticity will enable us to
574 make more accurate predictions about ecological interactions at various spatial and temporal scales. This will
575 prove to be of vital importance as our time to understand nature runs out, especially at the places where the
576 impacts of climate change and habitat loss hit harder.

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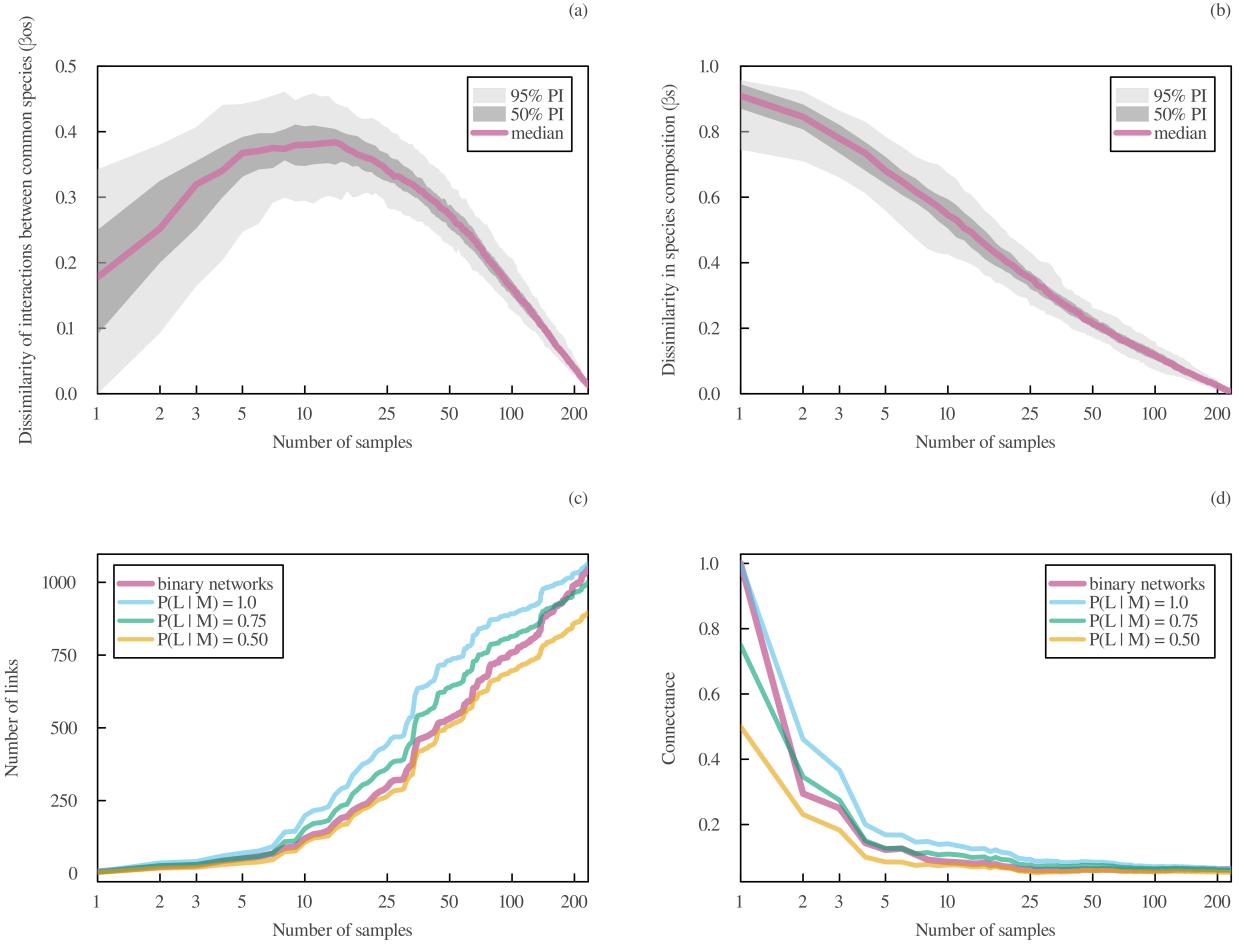


Figure 1: Network accumulation curves. (a) Dissimilarity of interactions between common species and (b) dissimilarity in species composition between aggregated local webs and the binary metaweb of host-parasite interactions. Aggregated local webs were obtained by sequentially and randomly selecting a number of binary local webs and aggregating both their species and interactions. In both panels, the colored line represents the median dissimilarity across simulations and the grey areas cover the 50% and 95% percentile intervals. (c) Scaling of the number of links and (d) scaling of connectance with the number of sampled binary and probabilistic local webs. For a better comparison with binary webs, local probabilistic webs were derived from the probabilistic metaweb with a false positive and false negative rate of zero. A specific value of $P(L|M)$ (the local probability of interaction among potentially interacting species) was used for all local webs within a particular curve. Aggregated probabilistic local webs were obtained by sequentially and randomly selecting a number of probabilistic local webs and aggregating both their species and interactions (with the value of $P(L|M)$ adjusting according to eq. 6).

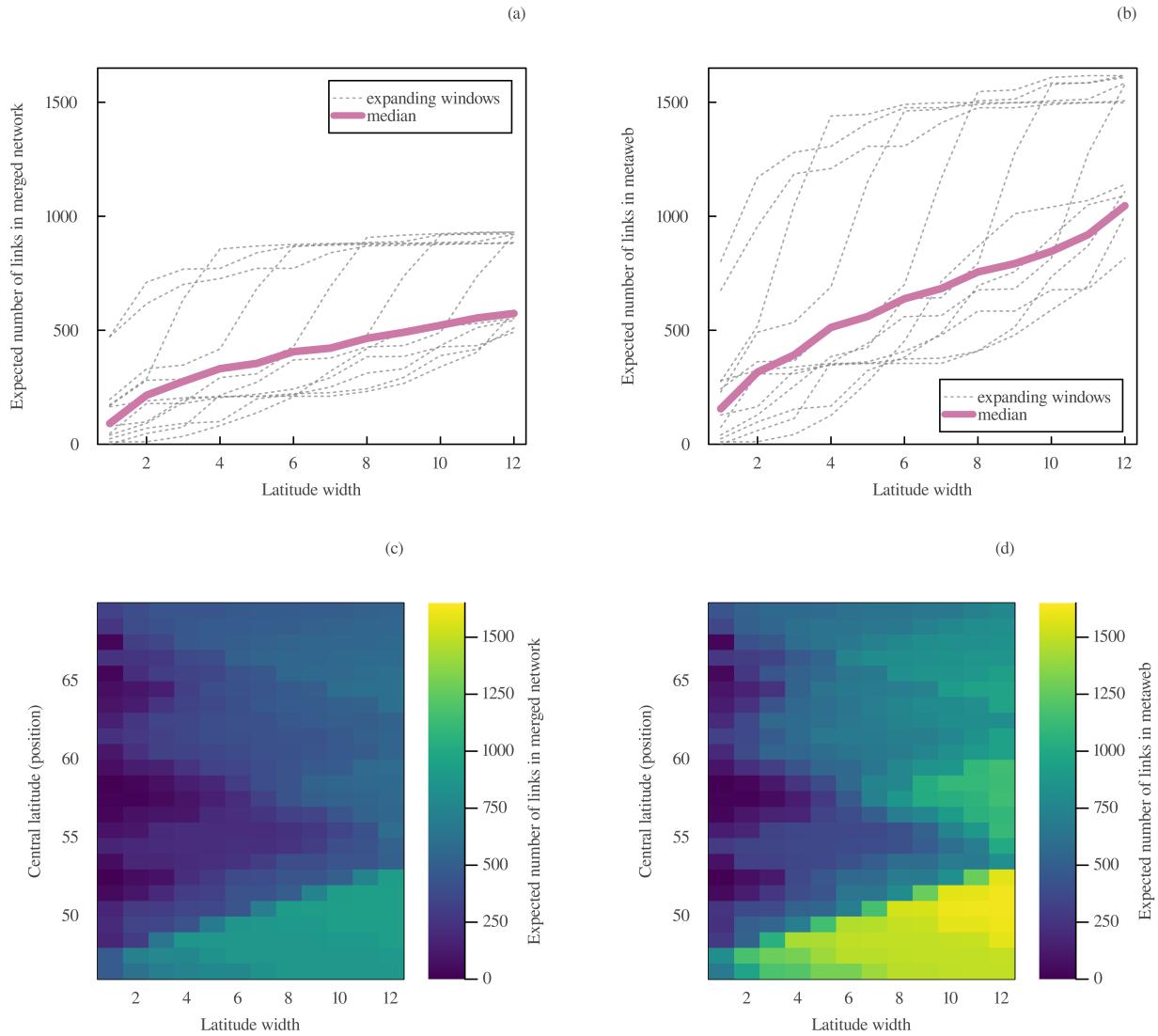


Figure 2: Spatial scaling of interactions. Expected number of host-parasite interactions in a network aggregating all probabilistic (a) local and (b) regional interactions within a latitudinal window of a given length. Every dashed curve corresponds to a different expanding window characterized by a different central latitude, with the colored solid line representing the median number of interactions. Heatmaps of the expected number of (c) local and (d) regional interactions found in windows of specified length and central latitudes. Probabilities of regional interactions were obtained with a false positive rate of 5% and a false negative rate of 10%. Local probabilistic interactions were derived from the probabilistic metaweb by setting the value of $P(L|M)$ (the local probability of interaction among potentially interacting species) to 1, ensuring a conservative comparison between aggregated local webs and metawebs. Aggregated local webs were obtained by aggregating both the species and interactions found within a particular latitudinal window, with the values of $P(L|M)$ remaining at their maximum value of 1 following eq. 6.

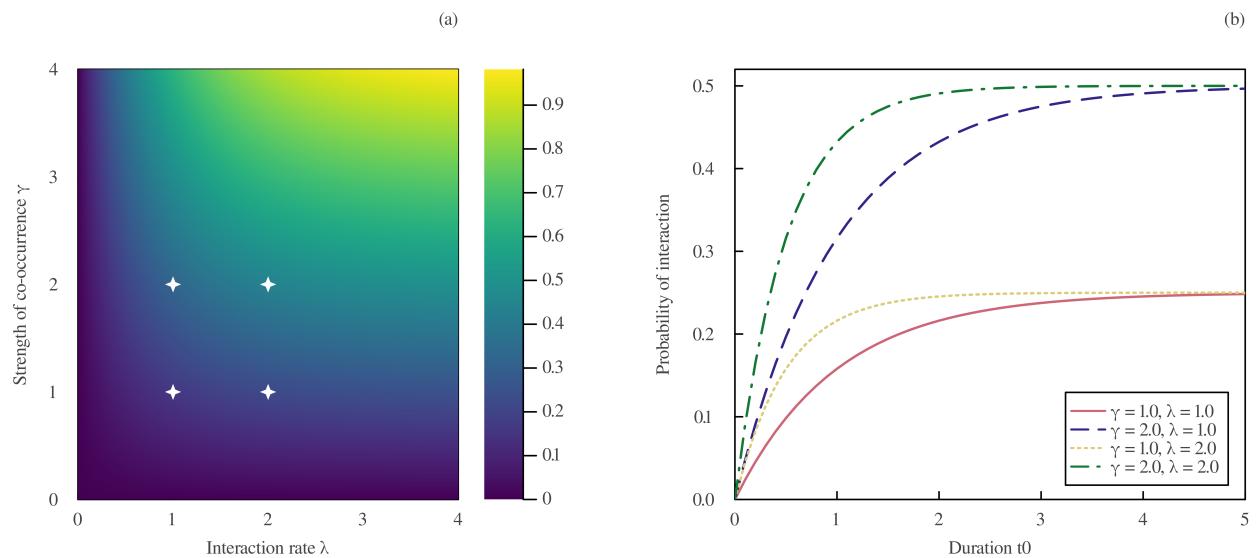


Figure 3: **Parameters of the spatiotemporally explicit model of interactions.** (a) Probability of local interaction given by the process model (eq. 12) under different values of λ and γ , with $t_0 = 1$. The parameter values used in the right panel are denoted by the white stars. (b) Scaling of the probability of interaction with the duration parameter t_0 in eq. 12, for different values of λ and γ . In both panels, the individual probabilities of occurrence $P_i(x, y, z)$ and $P_j(x, y, z)$ are set to a constant value of 0.5.

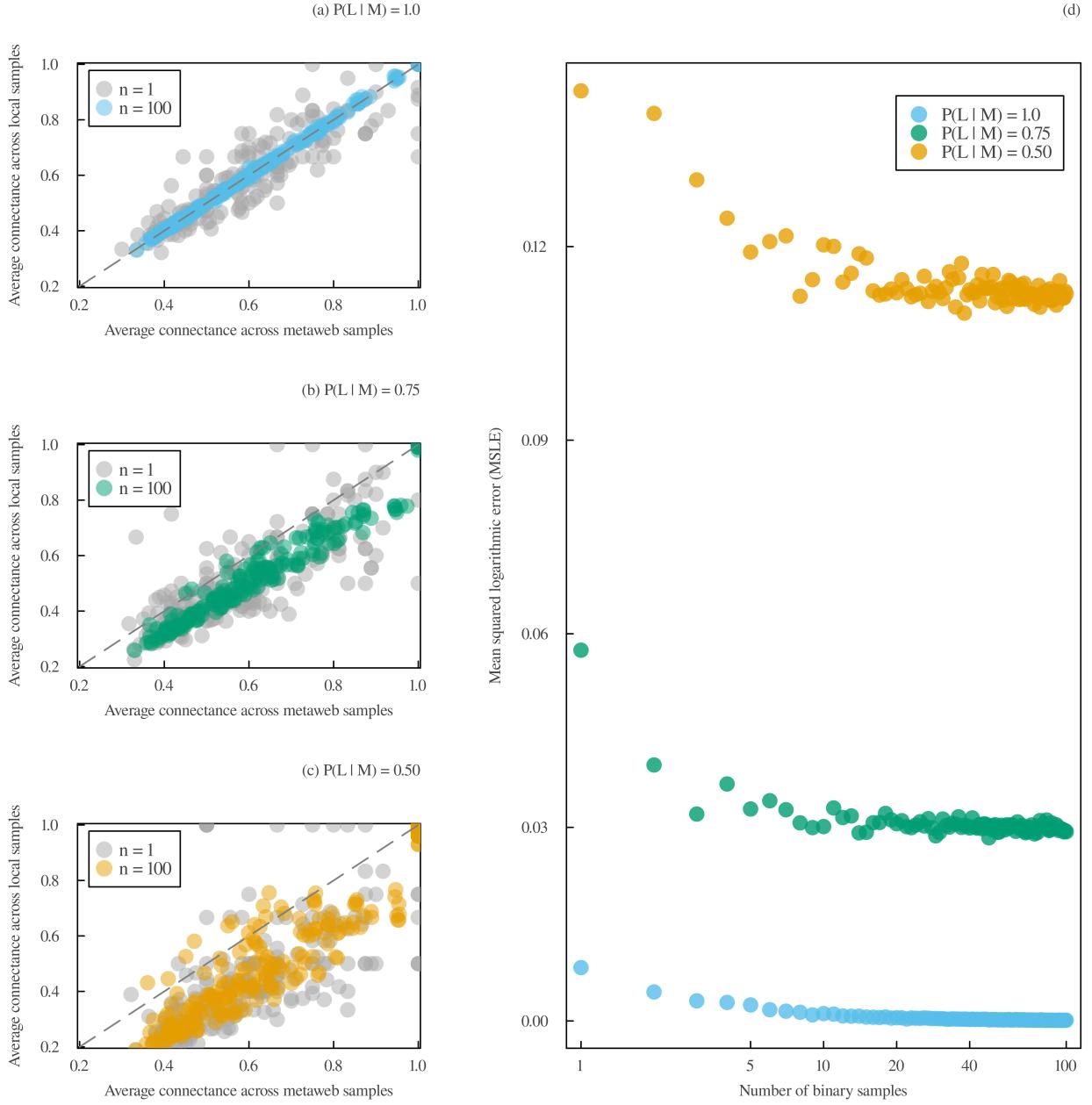


Figure 4: Connectance of sampled binary webs. Comparison between the average connectance of binary network samples obtained from the probabilistic local and metawebs. Each dot corresponds to a different site. The local probability of interaction between potentially interacting species was set to three different values: (a) $P(L|M) = 1.0$, (b) $P(L|M) = 0.75$, and (c) $P(L|M) = 0.50$. Grey dots represent the outcome of a single trial, while colored dots represent the average connectance of each network across 100 trials. (d) Reduction in the mean squared logarithmic error between the average connectance of binary networks obtained from these two sampling methods as the number of trials increases, for the same values of $P(L|M)$ used in panels a-c. Probabilities of regional interactions were obtained with a false positive rate of 5% and a false negative rate of 10%. Metaweb samples were obtained by randomly sampling binary interactions from the probabilistic metaweb, and then propagating this result to all local webs that include the species potentially engaged in the interactions. Local binary webs were generated by independently sampling binary interactions for each local probabilistic web.