Unveiling the Complexity of Food Webs: A Comprehensive Overview of Definitions, Scales, and Mechanisms

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Abstract

Food webs are a useful abstraction and representation of the feeding links between species in a community and are used to infer many ecosystem level processes. However, the different theories, mechanisms, and criteria that underpin how a food web is defined and, ultimately, constructed means that not all food webs are representing the same ecological process. Here we present a synthesis of the different assumptions, scales and mechanisms that are used to define different ecological networks ranging from metawebs (an inventory of all potential interactions) to fully realised networks (interactions that occur within a given community over a certain timescale). Illuminating the assumptions, scales, and mechanisms of network inference allows a formal categorisation of how to use networks to answer key ecological and conservation questions and defines guidelines to prevent unintentional misuse or misinterpretation.

At the heart of modern biodiversity science are a set of concepts and theories about biodiversity, stability and function. These relate to the abundance, distribution and services that biodiversity provides, and how biodiversity – as an interconnected set of species – responds to multiple stressors. The interaction between species (or individuals) is one of the fundamental building blocks of ecological communities provide a powerful abstraction that can help quantify, conceptualise, and understand biodiversity dynamics, and ultimately, one hopes, make prediction, mitigate change and manage services [ref]. Such network representations of biodiversity (including within species diversity) are increasingly argued to be an asset to predictive ecology, climate change mitigation and resource management. Here, it is argued that characterising biodiversity in a network will allow deeper capacity to understand and predict the abundance, distribution, dynamics and services provided by multiple species facing multiple stressors.

However, the way that a network is constructed (encoded) defines an epistemology of the network concept which, we argue, can influence the resulting observations and conclusions about pattern and mechanisms that are made [1,2]. This process of constructing networks has two major pillars: the data and theory, the latter representing an expression of mechanism and process giving rise to patterns that emerge from collating interactions among species. Each of these pillars carries with it a set of practical, semantic and conceptual constraints that not only influence progress in making network ecology more valuable and potentially predictive, but help define the spatial, temporal and evolutionary scale of assumptions we make and predictions we might generate from the networks.

With respect to data, it is extremely challenging to actually record species interactions in the field [3,4]. Despite notable herculean efforts (**Woodward? Benguela?** [5]), actual coverage of ‘real world’ interaction data remains sparse [6]. Against this practical challenge, there is additionally high variance in the terminology we use to define networks. Finally, the mathematical and statistical tools we use to construct, conceptualise, analyse and predict with these networks are also highly variable.

1. what are the underlying assumptions about nodes, edges, scale and process that are made when we attempt to delimit and describe a food webs;
2. are there families of commonly used tools that map onto assumptions about scales and processes;

The provision of this detail ultimately leads to a set of insights and conclusions about whether, when and under what conditions network representations of biodiversity can contribute to the advancement of ecological theory and generate value in predictive ecology. Specifically, we finish this perspective with an overview of fundamental questions in ecology that we think can benefit from network thinking and a proposal that such thinking can accelerate our capacity to predict the impact of multiple stressors on biodiverse communities.

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| Box 1 - Why we need to aggregate networks at different scales: A hypothetical case study |
| Although it might seem most prudent to be predicting, constructing, and defining networks that are the closest representation of reality there are pros and cons of constructing both realised networks as well as metawebs. Let us take for example a community across time/through seasons. In this community we expect species to be either present or absent depending on the season (*i.e.,* changes in co-occurrence) as well as some species exhibiting seasonal diet shifts, these details would be lost at the scale of the metaweb an it would be valuable to construct either smaller metawebs for the different seasonal communities (thereby capturing the changes in community diversity), or realised networks for each season (to capture diet or ecosystem process shifts). However, these small-scale networks lack the context of the bigger picture that is available at the metaweb - that is it gives us a more holistic idea of the entire diet range of a specific species, which is important when one needs to make conservation-based/applied decisions (*e.g.,* conserving the entire diet of a species and not just seasonal prey items) as well as providing information on interactions that may be possible regardless of the environmental/community context (species may have the capacity to consume certain prey items but do not do so due to local conditions). With this is mind let us see how the different network aggregations can be used  **1: A global metaweb**  Knowledge of the entire diet breadth of a species is valuable especially in terms of understanding how a species will respond to changes in the community - *e.g.,* invasions/rewilding exercises (where does the new species ‘fit’ within the network?) as well as potential capacity to shift its diet. ALthough this might make sense across space and not time but certain species act as links across the landscape [Rooney]  **2: A seasonal metaweb**  Knowledge at the finer scale is also valuable to understand/identify that there are in fact differences between the seasons  **3: A seasonal realised network**  Dynamics are useful because they are a representation of the different configurations/energy flows/ecosystem processes. Also to detect more nuanced shifts in diet - *e.g.,* seasonal diet shifts.  **Data trade off**  Above we highlight the practical uses of the different network configurations but we also need to take into consideration the barriers to construction/associated data needs/cost and acknowledge them. Basically in the ideal world we would have all this information at hand but in reality we might be sitting with seasonal metawebs… |

# 1. Setting the Scene: The Not So Basics of Nodes and Edges

Defining a food web seems simple; it is the representation of the interactions (edges) between species (nodes), however the definition of ‘edges’ and ‘nodes’, as well as the scale at which they are aggregated can take many forms [7]. An awareness of variance in the way a food web can be defined is critical as it represents the ‘object’ that is used to make inferences either about the interactions between species, or how the structure influences ecosystem level processes. One thus needs to be aware of both the criteria that is used to define nodes and edges, and what processes or mechanisms the aggregation of the two represents, as this will ultimately determine and delimit the way in which a network should be used.

### 1.0.1 How do we define a node?

Although this may seem an elementary question in the context of food webs — a node *should* represent a (taxonomic) species, the reality is that nodes can often represent an aggregation of different species - so called ‘trophic species’ or segregation of species by life stages. Representing nodes as non-taxonomic species can be useful in certain contexts [8,9] and in cases where the adult and larval stages of a species have different diets it may make ecological sense [10] meaning that it is not uncommon that networks often have nodes that have different definitions of a ‘species’ *e.g.* consisting of both taxonomic and trophic species. Practical implications of how we are aggregating the nodes is that the resolution may not always be ‘pixel perfect’ *i.e.,* we may be unable to assess the co-extinction risk of a species pair, however there is value in having nodes that represent an aggregation of species, as these convey a much more general overview of how the links are distributed within the community.

### 1.0.2 What is meant by an edge?

At its core, links within food webs can be thought of as a representation of either feeding links between species - be that realised [11] or potential [12], or representative of fluxes within the community/system *e.g.,* energy transfer or material flow [13]. How we specify links will influence the resulting structure of the network - and the inferences we will make thereof. For example taking a food web that consists of links representing all *potential* feeding links for a community (*i.e.,* a metaweb) will be meaningless if one is interested in understanding the flow of energy through the network as the links within a metaweb do not represent environmental/energetic constraints. In addition to the various ways of defining the links between species pairs there are also a myriad of ways in which the links themselves can be quantified. Links between species are often treated as being present or absent (*i.e.,* binary) but it is also possible to use probabilities [which quantifies how likely an interaction is to occur, 14,15] or continuous measurements [which quantifies the strength of of an interaction, 16].

### 1.0.3 Network representations

Broadly, networks can be thought of to fall into two different ‘types’; namely metawebs; traditionally defined as all of the *potential* interactions for a specific species pool [12], and realised networks; which is the subset of interactions in a metaweb that are *realised* ‘on the ground’. The fundamental difference between these two different types of networks is that a metaweb provides insight as to the viability of an interaction between two species occurring and is a means to identify links that are not ecologically plausible, *i.e.,* forbidden links [4], or an idea of the *complete* diet of a species [17]. Although metawebs are typically ‘constrained’ to a collection of species that also co-occur, there is no reason that a metaweb can include species that do not co-occur (although this would require some degree of prediction/assumption to identify those possible interactions). In contrast realised networks are highly localised and contingent on both the co-occurrence of species as well as the influence of the environment, and population and community dynamics on predator choice. In the context of definitions and semantics the links that are represented by a metaweb and a realised network are different; links that are absent in a metaweb can be treated as being truly absent, however links that are absent in a realised network cannot be considered to be truly absent but are rather as absent due to the broader environmental/community context. Thus, metawebs and realised networks are representing different mechanisms that are determining and constraining both the interactions between species as well as the resulting network structure, specifically providing context as to either the *potential* of an interaction occurring between two species (metawebs) or the subset of potential interactions that are *realised* in the filed (realised networks).

# 2. From Nodes and Edges to Scales, Context, and Processes

Armed with these basics, it is now possible to review the scales and assumptions that are made by a wide range of tools to assist in constructing networks against poor data with the hope of capturing important processes that underpin accurate prediction. Our thesis centres on a five-tier conceptualization of networks: evolutionary compatibility, co-occurrence, feasibility, abundance, predator choice, and non-trophic interactions. In the following sections we review each of these and then provide a synthesis among them.

## 2.1 Understanding the processes that determine species interactions

Processes that are all-or-nothing (possibility) vs processes that are context dependent (likelihood). Processes form the underlying logic of models (and ~~arguably~~, no, for sure even empirical data). This means also the interplay of the two, *i.e.,* the use of models to ‘gap fill’ within existing empirical dataset [18,19]. Ultimately when we put this all together it will influence how we can (and should) use the resulting network. Here we present [Figure 1](#fig-feasibility) some of the processes that have been shown to influence either/or the feasibility (possibility) of an interaction occurring between two species or if a feasible interaction is realised (likelihood of realisation) within the specific environmental/community context. Of course these processes do not function in a vacuum and do interact with/influence one another but it is still beneficial to present them as such as these are often the underlying processes that influence model development, the criteria for data collection in the field, and the scale of organisation for which they are relevant (species, population, community).

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| Figure 1: TODO. |

**Evolutionary compatibility**

There is compelling evidence that the possibility of an interaction occurring between two species is the result of their shared (co)evolutionary history [20–22]. In the more proximal sense this is manifested as the ‘trait complementarity’ between two species, whereby one species (the predator) has the ‘correct’ set of traits that allow it to chase, capture, kill, and consume the other species (the prey). For species pairs where this condition is not met the link is deemed to be forbidden [4]; *i.e.,* not physically possible and will always be absent within the network. In the context of trying to determine the feasibility (*i.e.,* the *possibility*) of an interaction, phylogeny is an excellent predictor [23,24] and allows one to construct what can be considered to be a metaweb. In terms of thinking about the anatomy of an ‘feasibility network’ one should be aware that it is possible to represent interactions as either binary (feasible/forbidden; *i.e.,* the traditional definition of a metaweb [12]) or as a probability [15], where the probability represents how likely that the interaction between to species is feasible (what is the possibility of this interaction occurring?).

**(Co)occurrence**

Although the outright assumption that because two species are co-occurring it must mean that they are interacting is inherently flawed [25], it is of course impossible for two species to interact (at least in terms of feeding links) if they are not co-occurring in time and space. Thus co-occurrence data alone is insufficient to build an accurate and ecologically meaningful representation of a food web having information on the co-occurrence of species can further aid us in refining metawebs by allowing us to downsample the network based on the species found in a specific location, or even add additional uncertainty based in how likely species are to co-occur [26]. Additionally the interplay between the interaction between a species pair and their co-occurrence is meaningful when one is operating in the space of trying to determine the distribution of a species [27], and forms a key component of some of the next generation species distribution models *e.g.,* joint SDMs [28].

**Abundance**

The abundance of the different species within the community can influence the likelihood of an interaction occurring in a myriad of ways. There is the argument that networks (and the interactions that make them up) are driven by only the abundance of the different species and not the characteristics (traits), *sensu* neutral processes and have been formalised with the neutral model [29], as well as statistical tools [30]. Alternatively the abundance of species in a community can influence which interactions are ultimately realised [15,31].

**Predator choice (energetic cost)**

Ultimately, predator choice is underpinned by the energetic cost-benefit of trying to catch, kill, and consume prey, and is well described within optimal foraging theory [ref] and rests on the idea that the prey a predator chooses to target is one that will have the greatest return on energy with the lowest energetic cost. There are additional bodies of work that attempt to include the cost of movement that the environment imposes on an individual [32] as well as 2D/3D search space [33]. In terms of formalising these processes in the context of predicting networks using diet models [34,35] that have predator choice determined by the handling time, energy content, prey density, and predator attack rate. [36] developed a model that moves the energy of the system into different modules related to the process of the predator acquiring energy from the prey *i.e.,* compartmentation in food webs [37].

**Indirect interactions**

The realisation (presence/absence) or strength of trophic interactions themselves can also be modified by other, indirect (non-trophic), interactions [38,39], this can be either ‘directly’ through *e.g.,* competition or ‘indirectly’ *e.g.,* mutualistic/facilitative interactions will alter the fine-scale distribution and abundance of some species [40,41].

It should be self evident that the different processes discussed above are all ultimately going to influence the realisation of interactions as well as the structure of a network, however they are acting at different scales of organisation. Both the **co-occurrence** and the **evolutionary compatibility** are valid at the scale of the species pair of interest, that is the *possibility* of an interaction being present/absent is assessed at the pairwise level and one is left with a ‘list’ of interactions that are present/absent. Although it is possible to build a network (*i.e.,* metaweb) from this information it is important to be aware that the structure of this network is not constrained by real-world dynamics or conditions (*i.e.,* community context), just because species are able to interact does not mean that they will [31]. In order to construct a network who’s structure is a closer approximation of reality (localised interactions) one needs to take into consideration properties of the community as a whole and not just the two species of interest.

**downsampling paragraph??**

# 3. Network prediction is nuanced

The different models that are used to either predict or construct networks have an underlying philosophy that often only captures one or a few of the processes discussed in [Section 2.1](#sec-process), has implications for how the resulting network is defined [Section 1](#sec-anatomy), which will ultimately delimit and define what inferences can be made from the resulting network. Selecting a model for the task of network prediction should come down to two things; what *aspect* of a food web one is interested in predicting, and what data are available, necessary, and sufficient, and what is the purpose of wanting to predict a network? It is important that a researcher is aware of this to ensure that the appropriate model is selected. Broadly researchers will be interested in predicting/constructing two different types of networks; *metawebs*, which is essentially a list of all interactions that are *possible* for a specific community (*i.e.,* at the scale of the species pairs), or being able to predict location specific, *realised*, networks for the community (*i.e.,* at the scale of the community). The nature of metawebs means that they are unable to capture the structural metrics of realised/‘real-world’ networks [42]. The researcher is also constrained by the data needs of both the model as well as the network type; for example in order to predict a realised network one needs additional community/population level data (*e.g.,* abundance), making metawebs a more feasible choice in data-poor contexts (*e.g.,* [17] construct a metaweb using a species list and a phylogenetic tree). The final question is assessing the purpose of predicting a network - is it to create a series of simulated, species agnostic but still ecologically plausible, networks [*e.g.,*] or to predict a network for a specific community at a specific location. It is these three points that will ultimately dictate which model is going to best allow one to predict the appropriate network.

## 3.1 Models that predict structure

Although we identify mechanisms that determine species interactions in [Section 2.1](#sec-process) not all models that are used to predict networks operate at this ‘mechanistic’ level (at least in absolute terms), but rather represent the *structure* of a network based on a series of *a priori* assumptions of network connectance (*e.g.,* the niche model [9]; although see [43] for a parameter-free model) or other structural features of a *realised* network (*e.g.,* stochastic block model, [44]). Importantly these structural models do not make species specific predictions (they are usually species agnostic and treat nodes as trophic species) and so cannot be used to determine if an interaction is either possible *or* realised between two species (*i.e.,*one cannot use these models to determine if species eats species ). Although this means this suite of models are unsuitable as tools for predicting interactions, they have been shown to be sufficient tools to predict the structure of networks [45].

## 3.2 How do we predict food webs?

There as many ways to predict networks as what there is to define them and along with taking into consideration the points raised in the previous section it is also beneficial to think about the context in which the different models were developed - and how this will influence the networks that they produce… Also it is not feasibly possible to list every single approach that has been developed to predict networks and so we will present what we believe to be the broad families that represent the different approaches to predicting networks [Table 1](#tbl-families), particularly how these relate to the processes identified in [Section 2.1](#sec-process), as well as models that predict network structure (see [Section 3.1](#sec-network-build)).A more extensive overview of the different models that fall with in the different model families can be found in [SuppMat 1](https://beckslab.github.io/ms_t_is_for_topology/notebooks/model_descriptions-preview.html) and for a more detailed breakdown of the different ‘traits’ of the model families refer to [SuppMat 2](https://beckslab.github.io/ms_t_is_for_topology/notebooks/model_qualitative-preview.html).

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| Table 1: A summary of the different families of tools that can be used to generate food webs.   | Model family | Assumptions | Data/process | ‘Limitation’ | Network type | Key reference | | --- | --- | --- | --- | --- | --- | | null | Links are randomly distributed within a network |  | parameter assumptions, species agnostic | structural network |  | | neutral | Network structure is random, but species abundance determines links between nodes | abundance | parameter assumptions | structural network | [29] | | resource | Networks are interval, species can be ordered on a ‘niche axis’ |  | parameter assumptions, species agnostic | structural network | [45] | | generative | Networks are determined by their structural features |  | need real world networks | structural network |  | | energetic | Interactions are determined by energetic costs | abundance + energy | does not account for forbidden links in terms of evolutionary compatibility | ‘energy’ network |  | | graph embedding | Interactions can be predicted from the latent traits of networks | evolutionary compatibility | need real world networks | metaweb | [17] | | trait matching | Interactions can be inferred by a mechanistic framework/relationships | evolutionary compatibility | well studied species/communities | metaweb | [46] | | binary classifiers | Interactions can be predicted by learning the relationship between interactions and ecologically relevant predictors | evolutionary compatibility | need real world networks | metaweb | [47] | | expert knowledge | ‘Boots on the ground’ ecological knowledge and observations | evolutionary compatibility | well studied species/communities | metaweb |  | | data scavenging | Webscraping to create networks from online databases |  | need real world networks | metaweb | [48] (if you squint?) | | co-occurrence | co-occurrence patterns arise from interactions so we can use these patterns to reverse engineer the interactions | co-occurrence | does not account for forbidden links in terms of evolutionary compatibility or account for energy constraints | co-occurrence network |  | |

There is a bit of a ‘point of conflict’ between those calling for ‘pixel perfect’, regional scale data [11,49] and for the means to generate networks that are ecologically plausible *representations* (*sensu* structural networks). This represents two challenges; one is that models that represent generalisations of networks often lack the ability to retrieve any species/community specificity which limits their utility for real world, species-driven scenarios *e.g.,* species driven conservation efforts [50], however networks that are constructed through either (most) empirical observations or through predictive means are fundamentally going to represent metawebs, *i.e.,* lack constrained links, a representation of structure, or energy flow…

# 4. Making Progress with Networks

## 4.1 Further development of models and tools

As we show in [Table 1](#tbl-families) there has been a suite of models that have been developed to predict trophic links, however we are lacking in tools that are explicitly taking into consideration estimating both the feasibility as well as realisation of links, *i.e.,* both interactions and structure simultaneously [51]. This could be addressed either through the development of tools that do both (predict both interactions and structure), or it might be possible to do a ensemble modelling approach [52]. Alternatively the development of tools that will allow for the downsampling of metawebs into realised networks [*e.g.,* 53], although deciding exactly what is driving differences between local networks and the regional metaweb might not be that simple [54]. Probably also something that aligns with trying to predict interaction strength - because that would be the gold standard. Probably also worth just plainly stating that feasibility of developing a model that is both broadly generalisable, but also cas local specificity is probably not attainable [55]

## 4.2 At what scale should we be predicting/using networks?

Look at [56]

We lack a clear agenda (and conceptualisation) as to what the appropriate level of aggregation is for a ‘network’. Realistically most empirical networks are more aligned with metawebs as opposed to realised networks as they are often the result of some sort of aggregation of observations across time, this creates a two-fold problem. Firstly, we need to think about how this affects any sort of development of theory that sits closer to the ‘realised network’ side of the spectrum - how often are we trying to ask and answer questions about realised networks using feasible networks? The second is that this lack of ‘direction’ as to how we should define a network is (actually) probably one of the biggest barriers that is affecting the use of networks in applied settings… By define I mean both delimiting the time and geographic scale at which a network is aggregated at [57]. This is important because it can influence the inferences made, *e.g.,* the large body of work (landscape theory for food web architecture) that showcases how different species use the landscape will influence network dynamics [58]. There is also a bit of an interplay with time and data and the different scales that they may be integrated at - co-occurrence may span decades and just because two species have been recorded in teh same space does not mean it was at the same timescale [59]

## 4.3 How should we use different networks?

What for and how we can use networks is perhaps one of the biggest ‘gaps’ we have in network ecology (Tim’s EBV ms), and there is a serious need to start drawing clear, ecological links between network form and function [although see 60]. That being said one of the most important things we can do is to be aware of the parameter space that is possible given a specific definition of a network and operate within those parameters. And we should use this in how we also evaluate/benchmark the performance of the different models as well; [61] presents a set of guidelines for assessing how well a model recovers pairwise interactions but we lack any clear strategies for benchmarking structure.

## 4.4 Feasible, realised, or sustainable?

When do we determine a link to be ‘real’… In the context of feasible networks this is perhaps clearer - if all things were equal (*i.e.,* community context is irrelevant) would the predator be able to consume the prey. However in the realised space there is also the question of the long term ‘energetic feasibility’ of an interaction - just because an interaction is possible in the now is it able to sustain a population in the long term. And what is the scale for that long term - are we thinking at the generational scale? Because ultimately when we are constructing a network we are aggregating not only across space but also across time… This is probably again a Lokta-Volterra space question and something that the dynamic foodweb model [62–64] is addressing, but again it is integrating this with the feasible/realised axis.

# 5. Concluding remarks

I think a big take home will (hopefully) be how different approaches do better in different situations and so you as an end user need to take this into consideration and pick accordingly. I think [65] might have (and share) some thoughts on this. I feel like I need to look at [66] but maybe not exactly in this context but vaguely adjacent. This is sort of the crux of the argument presented in [59] as well.

Do we expect there to be differences when thinking about unipartite vs bipartite networks? Is there underlying ecology/theory that would assume that different mechanisms (and thus models) are relevant in these two ‘systems’.

* The [67] paper looks at some methods but is specifically looking at a bipartite world…

# References

1. Proulx, S.R. *et al.* (2005) [Network thinking in ecology and evolution](https://doi.org/10.1016/j.tree.2005.04.004). *Trends in Ecology & Evolution* 20, 345–353

2. Brimacombe, C. *et al.* (2023) [Shortcomings of reusing species interaction networks created by different sets of researchers](https://doi.org/10.1371/journal.pbio.3002068). *PLOS Biology* 21, e3002068

3. Jordano, P. (2016) [Chasing Ecological Interactions](https://doi.org/10.1371/journal.pbio.1002559). *PLOS Biology* 14, e1002559

4. Jordano, P. (2016) Sampling networks of ecological interactions. *Functional Ecology* DOI: [10.1111/1365-2435.12763](https://doi.org/10.1111/1365-2435.12763)

5. Maiorano, L. *et al.* (2020) [TETRA-EU 1.0: A species-level trophic metaweb of European tetrapods](https://doi.org/10.1111/geb.13138). *Global Ecology and Biogeography* 29, 1452–1457

6. Poisot, T. *et al.* (2021) [Global knowledge gaps in species interaction networks data](https://doi.org/10.1111/jbi.14127). *Journal of Biogeography* 48, 1552–1563

7. Poisot, T. *et al.* (2016) [Describe, understand and predict: Why do we need networks in ecology?](https://www.jstor.org/stable/48582345) *Functional Ecology* 30, 1878–1882

8. Yodzis, P. (1982) [The Compartmentation of Real and Assembled Ecosystems](https://doi.org/10.1086/284013). *The American Naturalist* 120, 551–570

9. Williams, R.J. and Martinez, N.D. (2000) [Simple rules yield complex food webs](https://doi.org/10.1038/35004572). *Nature* 404, 180–183

10. Clegg, T. *et al.* (2018) [The impact of intraspecific variation on food web structure](https://doi.org/10.1002/ecy.2523). *Ecology* 99, 2712–2720

11. Pringle, R.M. (2020) [Untangling Food Webs](https://doi.org/10.1515/9780691195322-020). In *Unsolved Problems in Ecology*, pp. 225–238, Princeton University Press

12. Dunne, J.A. (2006) The Network Structure of Food Webs. In *Ecological networks: Linking structure and dynamics* (Dunne, J. A. and Pascual, M., eds), pp. 27–86, Oxford University Press

13. Lindeman, R.L. (1942) [The Trophic-Dynamic Aspect of Ecology](https://doi.org/10.2307/1930126). *Ecology* 23, 399–417

14. Poisot, T. *et al.* (2016) [The structure of probabilistic networks](https://doi.org/10). *Methods in Ecology and Evolution* 7, 303–312

15. Banville, F. *et al.* (2024) [Deciphering probabilistic species interaction networks](https://doi.org/10.32942/X28G8Z)EcoEvoRxiv

16. Berlow, E.L. *et al.* (2004) [Interaction strengths in food webs: Issues and opportunities](https://doi.org/10.1111/j.0021-8790.2004.00833.x). *Journal of Animal Ecology* 73, 585–598

17. Strydom, T. *et al.* (2023) [Graph embedding and transfer learning can help predict potential species interaction networks despite data limitations](https://doi.org/10.1111/2041-210X.14228). *Methods in Ecology and Evolution* 14, 2917–2930

18. Biton, B. *et al.* (2024) Inductive link prediction boosts data availability and enables cross-community link prediction in ecological networks

19. Stock, M. (2021) Pairwise learning for predicting pollination interactions based on traits and phylogeny. *Ecological Modelling*

20. Segar, S.T. *et al.* (2020) [The Role of Evolution in Shaping Ecological Networks](https://doi.org/10.1016/j.tree.2020.01.004). *Trends in Ecology & Evolution* 35, 454–466

21. Gómez, J.M. *et al.* (2010) [Ecological interactions are evolutionarily conserved across the entire tree of life](https://doi.org/10.1038/nature09113). *Nature* 465, 918–921

22. Dalla Riva, G.V. and Stouffer, D.B. (2016) [Exploring the evolutionary signature of food webs’ backbones using functional traits](https://doi.org/10.1111/oik.02305). *Oikos* 125, 446–456

23. Strydom, T. *et al.* (2022) [Food web reconstruction through phylogenetic transfer of low-rank network representation](https://doi.org/10.1111/2041-210X.13835). *Methods in Ecology and Evolution* 13, 2838–2849

24. Fricke, E.C. *et al.* (2022) [Collapse of terrestrial mammal food webs since the Late Pleistocene](https://doi.org/10.1126/science.abn4012). *Science* 377, 1008–1011

25. Blanchet, F.G. *et al.* (2020) [Co-occurrence is not evidence of ecological interactions](https://doi.org/10.1111/ele.13525). *Ecology Letters* 23, 1050–1063

26. Dansereau, G. *et al.* (2023) Spatially explicit predictions of food web structure from regional level data

27. Higino, G.T. *et al.* (2023) [Mismatch between IUCN range maps and species interactions data illustrated using the Serengeti food web](https://doi.org/10.7717/peerj.14620). *PeerJ* 11, e14620

28. Pollock, L.J. *et al.* (2014) [Understanding co-occurrence by modelling species simultaneously with a Joint Species Distribution Model (JSDM)](https://doi.org/10.1111/2041-210X.12180). *Methods in Ecology and Evolution* 5, 397–406

29. Canard, E. *et al.* (2012) [Emergence of Structural Patterns in Neutral Trophic Networks](https://doi.org/10.1371/journal.pone.0038295). *PLOS ONE* 7, e38295

30. Momal, R. *et al.* (2020) [Tree-based inference of species interaction networks from abundance data](https://doi.org/10.1111/2041-210X.13380). *Methods in Ecology and Evolution* 11, 621–632

31. Poisot, T. *et al.* (2015) [Beyond species: Why ecological interaction networks vary through space and time](https://doi.org/10.1111/oik.01719). *Oikos* 124, 243–251

32. Cherif, M. *et al.* (2024) [The environment to the rescue: Can physics help predict predator–prey interactions?](https://doi.org/10.1111/brv.13105) *Biological Reviews* n/a

33. Pawar, S. *et al.* (2012) [Dimensionality of consumer search space drives trophic interaction strengths](https://doi.org/10.1038/nature11131). *Nature* 486, 485–489

34. Beckerman, A.P. *et al.* (2006) [Foraging biology predicts food web complexity](https://doi.org/10.1073/pnas.0603039103). *Proceedings of the National Academy of Sciences* 103, 13745–13749

35. Petchey, O.L. *et al.* (2008) [Size, foraging, and food web structure](https://doi.org/10.1073/pnas.0710672105). *Proceedings of the National Academy of Sciences* 105, 4191–4196

36. Wootton, K.L. *et al.* (2023) [Towards a modular theory of trophic interactions](https://doi.org/10.1111/1365-2435.13954). *Functional Ecology* 37, 26–43

37. Krause, A.E. *et al.* (2003) [Compartments revealed in food-web structure](https://doi.org/10.1038/nature02115). *Nature* 426, 282–285

38. Golubski, A.J. and Abrams, P.A. (2011) [Modifying modifiers: What happens when interspecific interactions interact?](https://doi.org/10.1111/j.1365-2656.2011.01852.x) *Journal of Animal Ecology* 80, 1097–1108

39. Pilosof, S. *et al.* (2017) [The multilayer nature of ecological networks](https://doi.org/10.1038/s41559-017-0101). *Nature Ecology & Evolution* 1, 101

40. Kéfi, S. *et al.* (2012) [More than a meal… integrating non-feeding interactions into food webs: More than a meal …](https://doi.org/10.1111/j.1461-0248.2011.01732.x). *Ecology Letters* 15, 291–300

41. Kéfi, S. *et al.* (2015) [Network structure beyond food webs: Mapping non-trophic and trophic interactions on Chilean rocky shores](https://doi.org/10.1890/13-1424.1). *Ecology* 96, 291–303

42. Caron, D. *et al.* (2024) [Trait-matching models predict pairwise interactions across regions, not food web properties](https://doi.org/10.1111/geb.13807). *Global Ecology and Biogeography* 33, e13807

43. Allesina, S. and Pascual, M. (2009) [Food web models: A plea for groups](https://doi.org/10.1111/j.1461-0248.2009.01321.x). *Ecology Letters* 12, 652–662

44. Xie, J.-R. *et al.* (2017) [Completeness of Community Structure in Networks](https://doi.org/10.1038/s41598-017-05585-6). *Scientific Reports* 7, 5269

45. Williams, R.J. and Martinez, N.D. (2008) [Success and its limits among structural models of complex food webs](https://doi.org/10.1111/j.1365-2656.2008.01362.x). *Journal of Animal Ecology* 77, 512–519

46. Morales-Castilla, I. *et al.* (2015) [Inferring biotic interactions from proxies](https://doi.org/10.1016/j.tree.2015.03.014). *Trends in Ecology & Evolution* 30, 347–356

47. Pichler, M. *et al.* (2020) [Machine learning algorithms to infer trait-matching and predict species interactions in ecological networks](https://doi.org/10.1111/2041-210X.13329). *Methods in Ecology and Evolution* 11, 281–293

48. Poisot, T. *et al.* (2016) [Synthetic datasets and community tools for the rapid testing of ecological hypotheses](https://doi.org/10.1111/ecog.01941). *Ecography* 39, 402–408

49. Pringle, R.M. and Hutchinson, M.C. (2020) [Resolving Food-Web Structure](https://doi.org/10.1146/annurev-ecolsys-110218-024908). *Annual Review of Ecology, Evolution and Systematics* 51, 55–80

50. Dunn, R.R. *et al.* (2009) [The sixth mass coextinction: Are most endangered species parasites and mutualists?](https://doi.org/10.1098/rspb.2009.0413) *Proceedings. Biological Sciences* 276, 3037–3045

51. Strydom, T. *et al.* (2021) [A roadmap towards predicting species interaction networks (across space and time)](https://doi.org/10.1098/rstb.2021.0063). *Philosophical Transactions of the Royal Society B: Biological Sciences* 376, 20210063

52. Becker, D.J. *et al.* (2022) [Optimising predictive models to prioritise viral discovery in zoonotic reservoirs](https://doi.org/10.1016/S2666-5247(21)00245-7). *The Lancet Microbe* 3, e625–e637

53. Roopnarine, P.D. (2006) [Extinction Cascades and Catastrophe in Ancient Food Webs](https://www.jstor.org/stable/4096814). *Paleobiology* 32, 1–19

54. Saravia, L.A. *et al.* (2022) [Ecological network assembly: How the regional metaweb influences local food webs](https://doi.org/10.1111/1365-2656.13652). *Journal of Animal Ecology* 91, 630–642

55. Stouffer, D.B. (2019) [All ecological models are wrong, but some are useful](https://doi.org/10.1111/1365-2656.12949). *Journal of Animal Ecology* 88, 192–195

56. Hutchinson, M.C. *et al.* (2019) [Seeing the forest for the trees: Putting multilayer networks to work for community ecology](https://doi.org/10.1111/1365-2435.13237). *Functional Ecology* 33, 206–217

57. Estay, S.A. *et al.* (2023) Editorial: Patterns and processes in ecological networks over space. *Frontiers in Ecology and Evolution* 11

58. Rooney, N. *et al.* (2008) [A landscape theory for food web architecture](https://doi.org/10.1111/j.1461-0248.2008.01193.x). *Ecology Letters* 11, 867–881

59. Brimacombe, C. *et al.* (2024) [Applying a method before its proof-of-concept: A cautionary tale using inferred food webs](https://doi.org/10.13140/RG.2.2.22076.65927)

60. Delmas, E. *et al.* (2019) [Analysing ecological networks of species interactions](https://doi.org/10.1111/brv.12433). *Biological Reviews* 94, 16–36

61. Poisot, T. (2023) [Guidelines for the prediction of species interactions through binary classification](https://doi.org/10.1111/2041-210X.14071). *Methods in Ecology and Evolution* 14, 1333–1345

62. Lajaaiti, I. *et al.* (2024) [EcologicalNetworksDynamics.jl A Julia package to simulate the temporal dynamics of complex ecological networks](https://doi.org/10.1101/2024.03.20.585899)bioRxiv, 2024.03.20.585899

63. Delmas, E. *et al.* (2017) [Simulations of biomass dynamics in community food webs](https://doi.org/10.1111/2041-210X.12713). *Methods in Ecology and Evolution* 8, 881–886

64. Curtsdotter, A. *et al.* (2019) [Ecosystem function in predator–prey food webs—confronting dynamic models with empirical data](https://doi.org/10.1111/1365-2656.12892). *Journal of Animal Ecology* 88, 196–210

65. Petchey, O.L. *et al.* (2011) [Fit, efficiency, and biology: Some thoughts on judging food web models](https://doi.org/10.1016/j.jtbi.2011.03.019). *Journal of Theoretical Biology* 279, 169–171

66. Berlow, E.L. *et al.* (2008) [The “Goldilocks factor” in food webs](https://doi.org/10.1073/pnas.0800967105). *Proceedings of the National Academy of Sciences* 105, 4079–4080

67. Terry, J.C.D. and Lewis, O.T. (2020) [Finding missing links in interaction networks](https://doi.org/10.1002/ecy.3047). *Ecology* 101, e03047