A pragmatic approach to make theoretical syntheses in ecology

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Abstract

In domains that develop axiomatically, theoretical syntheses have the role to describe which are these axioms and how scientific practice should be guided by them. However ecology develops pragmatically, that is, scientists propose a new understanding of the world by exploring, modifying and co-opting previously proposed models, seldom referring to axioms. Therefore a synthesis in ecology cannot rely on the enunciation of axioms and need to be based on the actual activity of ecologists. Here we present an approach to make a theoretical synthesis based on how frequently scientists use some models to learn about the world. We argue that a domain of study can be delimited around a scientific community studying a phenomenon and that this community has a frequency of use of some models. We identify these models by assessing how the most referred publications are cited in the studies made by this community. We also present the results of the first implementation of the proposed approach to a case study with the phenomenon of ecological succession. We found that there is no clear division between "classical" and "contemporary" succession and that neutral models are now being used to explain succession. We conclude that the use of the proposed approach can be used to synthesize and understand theories that develop pragmatically and it allows for analyses of how theories change depending on the research context.

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1. Introduction

There is evidence that the use and importance of theories is declining in the scientific activity in biology as a whole ([NRC] National Research Council, 2008), and ecology is not an exception (Marquet et al., 2014). There is no clearly agreed conceptual basis unifying all scientific activity in ecology (Scheiner and Willig, 2011; Marquet et al., 2014) and even though there were attempts to synthesize ecological theory (e.g. McIntosh, 1986; Pickett et al., 2010; Scheiner and Willig, 2011), these attempts were seldom referred by the community. Regardless of this lack of consensus, ecology has undergone intense conceptual and institutional development as a science for more than a century of history (Hagen, 1989).

All scientific activity is guided by our previous knowledge about the world, which means that all scientific activity needs to have a conceptual basis. However, it might be the case that, in ecology, such conceptual basis is not so easy to identify. In some views of scientific theories, the conceptual basis of a field of study can be easily synthesized by a set of axioms or laws – statements about the world assumed to be self-evident (Cartwright, 1997; Turchin, 2003). Under these views, models are constructs about the world deduced from these axioms and knowledge is generated by comparing phenomena with models. If a phenomenon is adequately represented by the model, and therefore behaves like the model, the axioms from which the models were deduced can be regarded as true for the world (Swoyer, 1991). Therefore, a synthesis enunciating a set of axioms and how they can be combined to generate new models, will be very useful and should help guide scientific activity in a way that it is conceptually unified.

This view of how axioms guide scientific practice might explain why most discussions about theory in ecology revolves around the existence and identification of laws. Two of the things learnt from these discussions are that (i) if there are laws that unify and guide scientific practice in ecology, ecologists seldom agree on what they might be (see Smart, 1968; Lawton, 1999; Rosenberg, 1985; Marquet et al., 2014; Colyvan and Ginzburg, 2003) and (ii)

knowledge in Ecology has been generated despite such disagreement (O'Hara, 2005; El-Hani, 2006). So, what guides scientific activity in ecology and how can we make a meaningful theoretical synthesis in this field?

The answer for these questions might be in the actual activities of ecologists. In (Travassos-Britto et al, submitted), we proposed that there are advantages in assuming a pragmatic view in ecology, among them the possibility of creating a theoretical synthesis that is not based on axioms but on the actual scientific practice. Under the pragmatic view, models can be combined according to their usefulness in learning about a phenomenon, regardless of the assumptions made by this model. This implies that a scientist, in trying to learn about a phenomenon of interest, can make use of any models available to her, even models that are not based on the same axioms (Cartwright, 1983). There are many different criteria for a model to be considered useful, including cognitive criteria (e. g. predictive efficacy, explanatory success, increased understanding) (Odenbaugh, 2005; Woodward, 2019) and social criteria (e. g. prominence of its proponents) (Winther, 2006). Finding out which of these criteria are being more frequently used in a field of study would undoubtedly reveal important aspects about the scientific practice of the field (e. g. its epistemological values, social biases) (Agazzi, 2004), but this information would reveal very little about the actual phenomenon. However, the set of models considered useful to learn about the phenomenon, regardless of what "useful" entails, could reveal properties of the field of study related to how scientists approach and see a specific phenomenon.

The set of models considered useful in a field of study is not defined by a single study but by all scientific studies aimed at learning about the phenomenon. Therefore, such a synthesis should be based on the models used by a community of scientists. Furthermore, because each individual study can be focused on specific aspects of the phenomenon, they might be referring to models that reveal important aspects of how the phenomenon is conceived in the specific context of that single study, but are not informative for all contexts in which the phenomenon is tackled. For this reason, the synthesis should be made by the most referred models collectively. Models that are frequently referred by

a scientific community may reveal, among other things, that the assumptions in these models seem particularly relevant to learn the phenomenon from this community point of view.

Here, we propose a methodological approach to identify and describe the most referred models used in the scientific activity intended to understand a defined phenomenon. We detail in the paper the assumptions of the approach, then we provide an example of the implementation of the approach on the phenomenon of ecological succession, as a case study. We describe the specific methodological decisions we made to implement the approach and the results obtained. We end up discussing the benefits of using it to identify the conceptual basis and discuss some theoretical implications of our results to ecological succession as an example of different insights the approach allows.

2. PATh - Pragmatic Approach to Theories

Our approach aims to identify the models used as conceptual basis to the scientific activity of a community to learn about a phenomenon. Here we will use a very broad definition of model, which is any statement or set of statements describing how the world is or how it works (Morgan and Morrison, 1999). This definition of model focusing on the actual meaning of the statements and less on the role it plays in the structure of a theory is shared by different views of theories (see Winther, 2016, for more on different views of theory). However, the notion that the value of a model is related more to its usefulness than to the extent in which it represents a phenomenon is particularly important in the pragmatic view of theories. Models valued by its usefulness implies in two other assumptions in our approach that are also aligned with the pragmatic view. Because models of a theory are no longer defined by its deductive relationship with the axioms enunciated in the theory, the strong tendency to describe models in a mathematical formalism is no longer present and therefore the statements that constitute a model may be presented in any language (verbal, computational, physical etc) (Cartwright, 1997). Furthermore, the deductive relationship between models and laws are no longer a criterion that defines if a model is part or not of a theory. A

model is part of a theory if a community effectively uses it to learn about the focal phenomenon. This triadic relationship between models, scientists studying the phenomenon and the phenomenon is also aligned with the pragmatic view of theories (Bailer-Jones, 1999; Morgan and Morrison, 1999; Giere, 2010). Therefore, our approach defines theory and assume components of theories accordingly with the pragmatic view of theories, hence, Pragmatic Approach to Theories (PATh).

The PATh also assumes that science works as a system (sensu Von Bertalanffy, 1973), which means that scientific activity has multiple separated components that interact and affect one another. Such interactions have been described in many ways, e. g. as cycles of normal science followed by paradigm shifts (Kuhn, 2012), as heterogeneous networks of actors (Latour, 2005) or as distributed cognitive systems (Giere, 2010). Our approach is agnostic on the details of the dynamics of science systems, provided that such dynamics includes the use of models.

The PATh consists of some fixed steps (Figure 1). However, each step can be executed by adopting different methods. Here, we describe the general steps of the approach and what each step is supposed to achieve. Afterwards we describe how we specifically implemented each step in a case study with ecological succession.

The approach we are proposing consists of the following steps:

(i) Definition of the phenomenon of interest: For natural sciences the object of interest is usually a phenomenon. Under the pragmatic view, scientific activity in the natural sciences is aimed at learning about natural phenomenon. Scientific studies about a phenomenon will refer to the phenomenon in some way. Defining the phenomenon of interest should make clear which terms are associated with the scientific activity aimed to learn about the phenomenon. With these terms it is possible to search for studies about this phenomenon.

(ii) Definition of the community studying the phenomenon: Which models are considered most useful to learn about a phenomenon can change

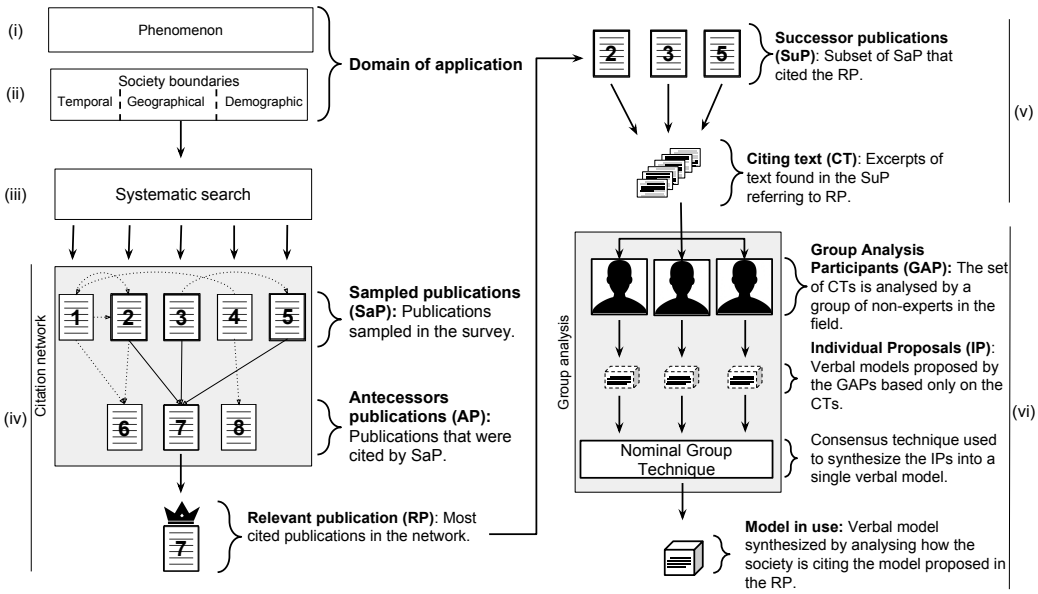

Figure 1: Workflow depicting how the information of obtained in each of the steps of the PATh (roman numerals) is used in the following step aiming to go from the definition of the domain of application to the final model.

from community to community. Therefore, before identifying which are the most useful models to learn about a phenomenon we must answer the question "the models considered useful by whom?". The set of models used by a single community can change with time and place. Also because communities can be heterogeneous in their use of models, depending on how we filter a community the frequency of use of some models also can change. Therefore, defining a community usually means defining temporal, geographical and demographic scopes. In defining specific geographical and demographic scopes one can understand how scientific activity changes from community to community. This implies that the PATh can be used to understand the impact of changes in such scopes in theoretical syntheses. By defining the phenomenon of interest and from whose point of view we want to approach it, we have the necessary information to decide which parameters will yield an adequate survey of the studies aimed at learning about the phenomenon. The definition of the phenomenon of interest and the community studying it, is the definition of the domain of application of the PATh.

(iii) Survey of the scientific activity: The goal of this step is to take a pic-

ture of what is being discussed by the community about the phenomenon of study. Publication of written articles is an important component of scientific activity related to validation of science itself (Latour, 2005) and most scientific activity is reported in written journals that can be accessed by most. Therefore, a survey of scientific activity can be done by operationalizing the decisions made in the first two steps into a systematic search of paper. It is important to notice that a systematic search is not the only way to identify the activities of the community studying a phenomenon. However, this is a well-known technique that has several tools already available to perform it and can be easily communicated among researchers (Bernard and Ryan, 2009).

(iv) Identification of relevant publication: The goal of this step was to identify the publication that were most referred to in the scientific activity of the community defined in step 3. There are different reasons for a publication to be cited, one of these reasons is to propose theoretical links among previous statements and new statements about the phenomenon of interest (Moravcsik and Murugesan, 1975; Cronin, 1984; Latour, 2005). Therefore, publications are of conceptual relevance to a field of study if it is cited by a significant fraction of the studies of this field by their statements about the natural world. We call these publications "relevant publications". There are two issues in separating the relevant publications from publications that have no conceptual value. The first issue to be considered is that many of the most cited publications were cited because they obviously supported the use of some statistical analysis. These publications need to be disregarded because despite being highly cited, these do not contribute to understanding how the community sees the phenomenon of interest. The second issue is that among the publications that were being cited by its statements about the natural world, there is a continuum that goes from the most cited to the least cited publication. Therefore, we needed an operational criterion to decide which publications would be included in the set of relevant publi-

cations. Because we want to identify those publications that were most cited but also were widely recognized in the domain, we chose a criterion that combined number of citations with representativeness. Ideally, the relevant publications set would be the minimum set that accumulates the larger number of citations by the scientific community analysed. By using such criterion one should identify a finite set of relevant publications that are frequently and widely cited by the community.

(v) Identification of citations: The goal of this substep is to identify, among all information described in the relevant publications, what is effectively being used by the community in their scientific activity and how it is being used. This can be done by carrying out a content analysis of excerpts of text found in the publications reflecting the activities of focal community, referring to the relevant publication. We do not propose an analysis of the relevant publications themselves because, aside from publications containing information that is not effectively used by its citing community, there could exist a significant difference between what is proposed in the relevant publication and the interpretation given by a reader (Drake et al., 2012). Because we are interested in what the citing community thinks of the publication and not what the original author intended to state, we propose an analysis of what is being said about the relevant publication in the studies carried out by the community. The result of this substep is a set of excerpts of text found in the studies of the community about the publication of interest.

(vi) Content analysis of citations: The goal of this substep is to rebuild self-consistent models based on the content of the citations of the relevant publications. The premise is that one should be able to identify the main statements that are working as conceptual bases for the studies of the community by reading a certain amount of citations of a publication that is frequently cited in this field of study, and identifying the similarities among these citations. These statements then can be synthesized in one or more verbal models representing the main contribution of

the relevant publication according to the community referring to them. If citations indicate that such statements are being used to support a further propositions about the world, the model identified as the most relevant contribution of the relevant publication is being used as a conceptual basis for this proposition. However, not all citations indicate that a statement about the natural world is being used to support a thesis. Therefore, the citation content also need to be surveyed regarding this issue. This analysis should disregard citations that are not contributing to the statement made by the study of the member of the community There are some situations in which this might occur, the citation might be describing a tool or method (operational), it might not be used to structure an argument (perfunctory), or it might be used as an example of something wrong (negational) (sensu Moravcsik and Murugesan, 1975). This final step should yield a set of models that were frequently referred by a scientific community to learn about the phenomenon of interest. Therefore, these models and be interpreted as the conceptual basis of this field of study according to this community. However, what these models will reveal about a field of study should change from field to field. Here we will present a case study using ecological succession as a study case to illustrate how the results of the approach can help us better understand the field of study.

3. A case study on ecological succession phenomenon

3.1. Defining the phenomenon of interest

We defined the phenomenon of interest as ecological succession in order to carry out a case study. We think the term "succession" is relatively unambiguous in ecology (see McIntosh, 1999). Therefore, instead of defining the phenomenon by its characteristics we are defining it by its name. In a way, we are interested in any phenomenon that is named "succession" in ecology. We realize that this definition will lead to a very inclusive criterion about what is ecological succession, but inclusive definitions are not problematic or uncommon in propositions of theoretical syntheses. For example, Pickett et al.

(2011) have given a definition that, as the authors state themselves, is very inclusive: "changes in structure or compositions of a group of organisms of different species at a site through time" (p. 187). We do not think that any use of the term "succession" in ecology will describe a phenomenon that is not contemplated by the definition given by Pickett et al. The approach, however, is robust to exceptions of this use, as we will see in the description of the following steps. We do realize that the way scientists refer to several phenomena can be more ambiguous and polysemous. In such cases, defining a phenomenon by its name or a single term might not be the best approach. Precisely because we think that ecological succession is a case of an unambiguous phenomenon within ecology, we chose it to exemplify an implementation of the PATh.

3.2. Defining the community

We decided that we wanted to identify the models of succession that are being used currently within the ecology. This definition help us define the time, geographical and demographic scopes. We understand that what is considered "current" is arbitrary. We decided that the present decade (at the time of the analysis) might be adequate scope of time considering the relatively long time a proposed model takes to change a field of study (see Mukherjee et al., 2017).

We did not restrict the geographical or demographic scope to a specific group within ecologists and we did not control for existent known biases (see Vessuri et al., 2014). Therefore, the results we obtained are as geographically and demographically biased as the publications found in the databases used in the analysis.

3.3. Surveying the scientific activities

In our implementation, we decided to search all publications that contained the term succession or successional in its title or abstract and were labelled by their authors as ecological studies in the past ten years from the date of the study. To do so we carried out a systematic search in the Web of Science database using the term "successi*" in the "Topic" field and filtered the publications that were in "Ecology" category, then we filtered the search for

publications dated from January 2007 to July 2017. This search resulted in 5,536 publications. These publications represent a sample of the documentation of the scientific activity about succession, in ecology of the past ten years.

3.4. Identifying of relevant publication

To identify the relevant publications we created a citation network using the software CitNetEplorer (van Eck and Waltman, 2014). Note that the publications describing the scientific activity of our selected community were dated from 2007 to 2017, but the publications cited in this activity could be from any year. The network created summed a total of 29,398 publications of different types (articles, books, chapters, proceedings papers, etc), with 245,210 connections among publications.

We excluded publications that were highly cited because they describe statistical tools. The most cited sources in this category were R Development Core Team (2008) (110 citations, 791 summing the citations of different editions), Sneath et al. (1973) (285 citations, 566 for all editions), McCune et al. (2002) (250 citations), Burnham and Anderson (2003) (230 citations), Zar et al. (1999) (197 citations). These publications were excluded from the network, because they did not describe any properties of the phenomenon of interest or the natural world. To select the relevant publications we added publications to the set of relevant publications sequentially from the most to the least cited until all 5,536 publications (reflecting the activities of the focal community) referred to at least one relevant publication in the set. However, after adding 100 publications to the relevant publications set, we observed that the proportion of 5,536 that cited at least one publication in the set tended to stability with much less than 100 publications. We executed this procedure considering only direct citations, considering direct and 2nd-degree citations (citations of citing articles), and considering direct, 2nd and 3rd degree citations. In all cases, there seemed to be a threshold tending to stabilization with 25 publications in the set of relevant publications (Figure 1). This stabilization showed that we would not reach a set of relevant publications that were cited by 100% of the

community. This analysis showed that about 20% of the papers that should reflect the scientific activities of the focal community were not citing the 100 most cited papers in the network. We were concerned that this fraction (20%) of the papers could be hiding a subcommunity cohesively citing another set of relevant publications not related to the ones most cited by the 80% of the community. We created, then, a second network containing only these 20% that did not cite the 100 most cited in the first network, amounting to a total of 954 publications. Afterwards we executed the same procedure to identify the most cited publications by these 20%. We discovered that the most cited publications in this smaller network were cited by only 6% of the 954 publications network. The stabilization of the relationship between the most cited publication set and the proportion of the 20% citing these publications was reached with only five publications. This result indicated that the fraction these 20% of the publications that should reflect this community activity did not form a cohesive sub community. Most likely, these publications are individually referring to lesser known models in the field of study without any convergence among them. Although we are considering these 20% as part of the community studying succession, they are not very useful to understand major tendencies in the community because they are not representative of the succession views.

The results of the analysis of this step indicates that the relevant fraction of the network refer to at least one of the models proposed in the 25 most cited publication (Table 1). We adopted the 25 most cited publications as the central ones in giving a conceptual basis for the studies of the defined community studying ecological succession.

3.5. Identifying citations

For each relevant publication we identified which studies of the community were citing it. Then we randomly selected publications in this list and searched for the excerpts of text in which the focal relevant publication was cited. We disregarded excerpts in which the relevant publication was cited in a group of other publications, because we wanted to be sure that the excerpt

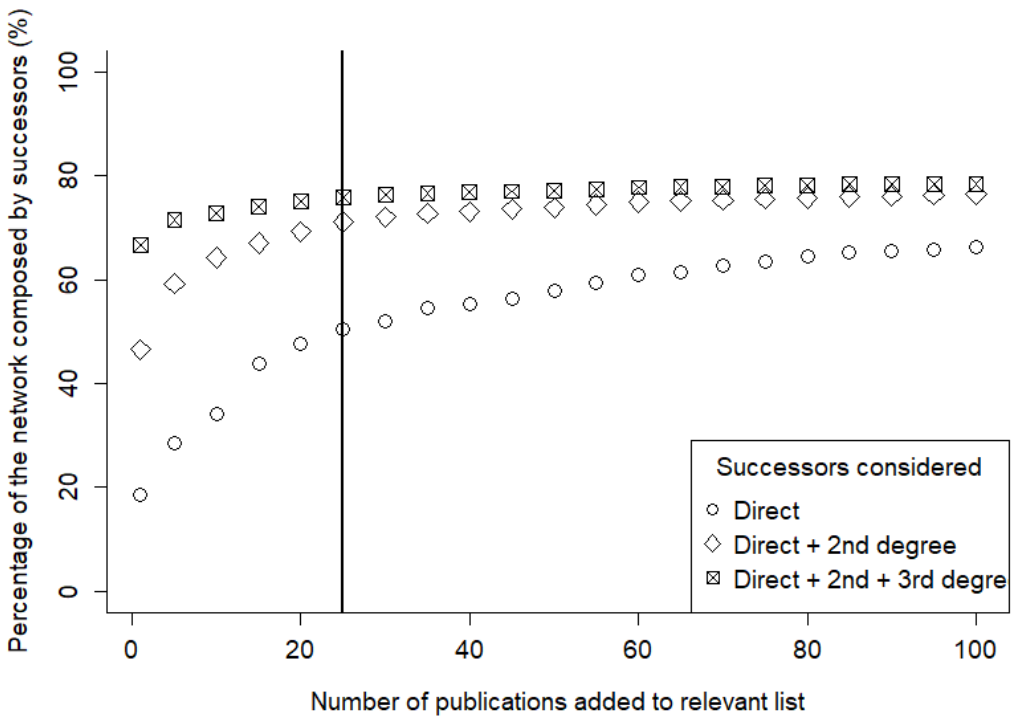

Figure 2: Stabilization of the relationship between the size of the relevant publications set and the percentage of sampled publications citing the set. These relationships were reached considering direct citation, direct and second-degree indirect citation, and direct, second- and third-degrees indirect citation. The vertical line indicates the threshold in which the citation proportion reaches stabilization for all three citation degree pf distances.

of text was specifically referring to the content of the focal relevant publication. Some studies of the community could have more than one excerpt of text that fitted the criteria or none. We separated the first 50 excerpts of text that fitted the criteria for each relevant publication. The 50 excerpts of text citing each relevant publication were submitted to a content analysis aimed to identify the main reasons each relevant publication was being cited. In a pilot analysis, participants declared that 50 excerpts of text was enough to execute the content analysis efficiently (see next section).

3.6. Analyzing the content of citations

This analysis was carried out by reading the excerpts of text and identifying the main reason a relevant publication was cited by the community as a whole. These reasons should be synthesized in a set of statements about the natural world. This statements are what we are considering verbal models of the world.

Table 1: List of relevant publications used in this worksorted by number of citations

Publication	**Number of citations**
Connell and Slatyer (1977)	780
Grime (1979)	468
Connell (1978)	400
Odum (1969)	374
Harper (1977)	343
Pickett and White (1985)	306
Grubb (1977)	294
Tilman (1988)	279
Egler (1954)	271
Cowles (1899)	266
MacArthur and Wilson (1963)	264
Bazzaz (1979)	207
Huston (1979)	203
Huston and Smith (1987)	200
Grime (1977)	198
Hubbell (2001)	189
Pickett et al. (1987)	183
Tilman (1987)	178
Watt (1947)	178
Huston and DeAngelis (1994)	177
Grime (1988)	176
Noble and Slatyer (1980)	171
Tilman (1985)	163
Shugart et al. (1984)	160
Guariguata and Ostertag (2001)	160

We realize that the interpretation of a single individual creating such synthesis might influence the final result. To deal with this issue, which is a recurrently ignored issue in most scientific studies (Daston, 1992) we used a technique that appeals to intersubjectivity as a key characteristic of the social processes of science. The technique's main characteristic is that more than one individual synthesized the models and their results were compared.

Each set of 50 excerpts of text citing a single relevant publication was read by three different people, that formed a trio. Each trio was responsible for

reading the excerpts of text of a set of three different relevant publications and synthesizing the main contribution of each. Therefore, to execute the synthesis to all 25 relevant publications we counted with the aid of 25 participants. From these 25 participants, all were graduated biologists, eight were Ph.D. in ecology (two professors and six post-doctoral fellows of the department of ecology) and 17 were graduate students (six Ph.D. candidates, and 11 master's degree candidates in ecology). Except by the two professors, all participants had no familiarity with most of the selected relevant publications. This was preferable to ensure that previous knowledge of the publication did not affect their interpretation of the citing excerpts of text. Nevertheless at the moment of the analysis the participants were not informed to what publication that set of excerpts of text were referring (the actual citations in the excerpts of text were replaced by "[Relevant Publication]" tag, to inform where in the sentence the relevant publication was referred to).

The participants in our study were to disregard citations that were considered by them as operational, perfunctory or negational. Some of these three excluded categories of citation could help to identify the main contribution of a relevant publication. However, if a publication is frequently cited in a negational way in a domain, for example, it is unlikely that the proposed model of this publication is being used as conceptual support to learn about the phenomenon of interest.

After each participant in the study in a trio had synthesized textually what they thought was the model or models being referred by the community, these three synthesis were compared in a consensus activity adapted from the "Nominal Group Technique (NGT)" (Bernard and Ryan, 2009). The goal of this activity was to synthesizing a verbal model or set of models that the three participants agreed as being what the citations of a relevant publication were referring to (see Supplementary Material II for methodological details of the activity). For the 25 relevant publications 29 textual models about the natural world were identified (all models are described in the Supplementary Material I).

4. Analysis of the resulting models

Through the PATh we were able to identify 29 textual models of the world that were frequently and widely referred to in studies about ecological succession contemporarily. The reason why each of these models is frequently being referred in this domain could reveal much about the structure of the theory of ecological succession and how the community sees the phenomenon itself. The conclusions we drew from analysing the set of models should illustrate the kind of information one can obtain by applying the PATh.

4.1. Defining ecological succession

In the search for the activity about the phenomenon, we did not executed a systematic search for the characteristics of a phenomenon we defined as succession, but by activities associated with the term "succession". In other words, we actually search for a phenomenon ecologists understand as succession. As a consequence, we can use the set of relevant models to define the phenomenon by the characteristics presented in the models. The models we identified make different statements about what ecological succession is and focus on different properties of the phenomenon. We, however, are not interested in particular views within the domain, but in how we can define succession phenomenon without excluding any of these models and at the same time being sufficiently informative for anyone who observe this phenomenon to conclude it is succession. To do so we conceived two propositions (sensu McGrath, 2014) that informed the conditions that seemed necessary and sufficient for any of the succession models observed in the set of models to occur. Then we conceived the third proposition that can explain why successions is such a diverse phenomenon.

The propositions that define succession, as viewed in the set of models identified through the PATh are:

Necessary and sufficient conditions

> **Proposition 1:** At each instant of time, there is a non-null probability that some amount of resource will be available for use.

Proposition 2: Organisms from different species or different ontogenetic stages have different probabilities of taking a fraction of the total resource units that become available. This difference can be due to (a) differential probabilities of colonization of a site; (b) different probabilities that the individuals in the site or their propagules take resource units.

Succession qualifiers

Proposition 3: The dynamics of the resource and the probabilities of the species taking resource units are contingent on the abundance of species in the community and environmental conditions.

These propositions are true for all conceived models of succession we identified as the most relevant in the domain. Considering that propositions 1 and 2 are necessary and sufficient for succession to occur means that in any situation in which it is observed that these conditions are true succession can occur, and likely is occurring. This information is not only useful to understand the field of study in which the PATh was applied. It helps ecologists decide if their phenomenon of study is succession or not, according to the focal community. This clarity should be used to avoid spurious debate, and be more direct in proposing changes to how we conceive the phenomenon.

Even though the models themselves might not have being conceived with these propositions explicitly in sight, they sure are concepts underlying the construction of models within the domain and by adopting them as true one could have conceived these models. Therefore, these propositions, in function, can be seen as fundamental principles of the domain. This means that any model that assumes these propositions as true is akin to the identified models and should be considered as a model within the domain of ecological succession as delimited by us.

Fundamental propositions of succession were made in the past and they were in accordance with ours in some respects, but in disagreement in others (Pickett et al., 2011). Nevertheless, in the propositions made by Pickett et al (2011), it is not clear why the authors selected those specific propositions, because there is no explicit method, like the one described here, linking propo-

sition to the actual activities of a scientific community. It is also not clear whether the authors were aiming at propositions that described the scientific activities in the field of study (like our), or aiming at propositions that prescribe how succession should be seen, according to the authors. We discuss some of these divergences in the next subsession.

4.2. Neutral models in succession theory

We noted that 5 of the 29 identified models did not include the word "succession" in their description. Three of these models came from references about the competition-colonization trade-off and its relationship to disturbance regimes (Models 4, 16 and 22, described originally in Connell 1978; Huston 1979; Watt 1947, respectively. See Supplementary material I). In the same vein, the two other models that did not mention succession explicitly are the related models of Island Biogeography and Neutral Theory, which describe the role of colonization and extinction in community assembly in general (Models 14 and 19, described in MacArthur and Wilson 1963; Hubbell 2001, Supplementary material I).

Even though these five cited relevant publications do not focus on describing or explaining the phenomenon of succession, they describe important concepts that are currently being used to make new proposition about how succession is and works, even though some of these processes seem at first not related to succession. For example, the domain of succession for many years was based soundly on niche theory (Pickett et al., 2010), but ecologists nowadays do consider insights from Hubbell's neutral theory when explaining succession. The evidence leading to this conclusion is not only the fact that Hubbell's paper was the 16th most cited (most than some considered classics) of the domain, but also the fact that, in the citing excerpts of text, the neutral model is frequently used to explain successional patterns at landscape or global scales. Similarly, the model of island biogeography is frequently used to explain why different patterns of succession emerge in fragments at varying distances from other fragments (see Supplementary Material III). These examples illustrate that the PATh allows the analysis of how some models,

conceived outside the scope of the phenomenon, are being used to understand the properties of the phenomenon there were possibly neglected before the proposal of these models. This example also strengthens our argument that scientific practice in ecology is done mostly in a pragmatic way.

4.2.1. Classical and contemporary views of succession

We also observed that the division between "classical" and "contemporary" views on succession is not as clear as it is depicted in some publications, including textbooks (e.g. Johnson, 1979; Pickett et al., 2005; Eliot, 2007; Pickett et al., 2011). It seems that concepts classified as being from the classical view are still used today to develop new models and concepts that were classified as contemporary were not a novelty and are still used very seldom. For example, when this division is made, in the "contemporary" view, succession is individualistic, while in the "classical" view succession is supra-individualistic. Individualistic succession means that succession is essentially the exchange of individuals, in the sense that any pattern observed is just the result of interactions among individuals. Supra-individualistic succession means that the agents of succession can be communities, functional groups or other supra-individual entities, and, therefore, succession occurs as these entities change in time (Myster and Pickett, 1988). The high frequency of citation of models considering supra-individual entities as the agents of succession (models 6 and 29, Supplementary Material I. See Odum, 1969; Guariguata and Ostertag, 2001) shows that models of succession in which supra-individual entities are the agents are also contemporary, and, moreover, are not currently rare.

Odum's 1969 seminal article is the 5th most cited publication in a network of more than five thousand publications constructed using the PATh. This paper is frequently cited in order to support the idea that succession is the change in ecosystem properties through time. Hence, there is little doubt that the scientific community studying succession still adopts supra-individual approaches to this phenomenon as a possible way to understand it. Similarly, Guariguata and Ostertag (2001) is used to give support to the claim that succession can be viewed as changes in functional groups.

It was stated that the classical view of succession modeled primary producers communities, while the contemporary view modeled different trophic levels (Pickett et al., 2005, 2011). Models of succession considering other trophic levels are hardly a novelty in the field and therefore not only a contemporary view (e. g. Shelford, 1911; Frankland, 1992; Kivi et al., 1993; Wieczorek and Todd, 1998; Bardgett et al., 2007)One could argue that although they were proposed in the past, only in contemporarily they are gaining attention. However, this does not seem the case. Such models do have received little attention in the past compared to models of plant succession (McIntosh, 1999), but this attention has not seem to have increased as none of the relevant models we identified had more than one trophic level in their communities. Therefore, the change to a more contemporary view where models of succession consider more than one trophic level is not happening.

In synthesis, some concepts classified as belonging to the "classical view" have been still used often as a conceptual basis for developing new propositions about succession in the last decade, while some concepts classified as belonging to the "contemporary view" have not been frequently used. This result leads to the question of whether this classification of concepts as belonging to classical and contemporary views on succession is a description of how the community understands the theoretical development of this field or a prescription of how it should be. These observations showed some insights we have on the theoretical structure of the succession domain, but there are many more results that can be explored. For example, disturbance, competition, trade-off were mentioned in many models. What is the partial role of each concept in the models identified? The neutral models seemed to be relatively new in the domain, since there are no models of neutral succession among the most cited. Is there an explicit neutral model of succession in the domain that is gaining visibility? Could ecosystemic views of succession (see Model 6 Odum, 1969) be related to recent increasing visibility of studies with carbon stock and sequestration. These are all interesting points to discuss but their discussion would greatly exceed the aim of this paper. We plan to discuss this results in the scope of successional ecology in further studies.

5. Benefits of the PATh

5.1. A pragmatic analysis of model use in a domain.

The PATh can be used to understand how models are being used within a domain and between domains. For example, some of the most used models within the domain of ecological succession are used frequently and come from publications that are among the most cited of the whole domain of ecology (MacArthur and Wilson, 1963; Odum, 1969; Tilman, 1985; Hubbell, 2001). It would not be surprising if these publications are relevant publications in other domains seemingly unrelated to the domain of ecological succession. If, in fact, these publications are relevant publications in other domains, this implies that some models are encompassed by two or more theories that have something in common. For example, the model of island biogeography is used frequently to understand the phenomenon of succession. However, it seems that this model is also particularly important to understand phenomena related to habitat fragmentation (Saunders et al., 1991; Fahrig, 2003). It might be that the domains of ecological succession and landscape ecology overlap in many different aspects. If an application of the PATh to the domain of landscape ecology reveals that the model of theory biogeography is in fact a relevant one, we would be sure that these domains are strongly linked – since its a relevant model in both domains – by at least this model.

Another scenario that the PATh allows us to detect is the existence of sub-domains within the focal domain. Sub-domains are clearly divided communities studying the phenomenon from points of views that are conceptually different. For example, Pickett et al. (2011) stated that in the contemporary view of succession the agents of the succession are individuals. Indeed, most of the models resulting from the application of the PATh are models about the interaction of individuals. However, some of the resulting models clearly described succession as a process that can happen at supra-individual levels and were frequently used currently to support succession studies (e.g. Model 6 and Model 29, Supplementary Material 1). This indicates that the domain can be divided into models that assume the individualistic view of succession

and models that assume that succession is a process that can happen at the community level. According to the propositions we elaborated both individualistic and non-individualistic approach would be considered as succession. However, one might want to understand only the phenomenon of succession as an individualistic process. From our point of view, this is a specific type of succession. Therefore, the community studying this phenomenon would also be a subset of the community we are focusing on this study. This information could be used to understand how the community studying succession is divided and in which aspects they diverge. Promoting more dialog between these two communities could lead to definitions that are common ground making the domain more unified.

5.2. Historical, geographical and demographic analyses of domains

We included historical, geographical and demographic parameters in the methodological decision because the views about a phenomenon may change from time to time and place to place and community to community (Basalla, 1967; Kuhn, 2012). Multiple applications of the PATh can be used to assess these changes.

On the one hand, because it takes time for a model to be analyzed and widely recognized by the scientific community, a model presented this year has little chance to be as frequently used as a model presented many years ago. On the other hand, models that are frequently referred to in the present might not be as well recognized in the future. The consequence of this process is that the resulting models identified by the application of the PATh are contingent on a given time frame. The application of the PATh at different time frames through history will show which models are the most used through time. For example, apparently the work of Clements (1916) was one of the most influential of succession at some time (McIntosh, 1999). At this first implementation of the PATh, we detected that Clements (1916) was not among the 25 most cited publications. Indicated that currently his model was not that influential. However, his model was still among the 50 most cited publications. We checked some excerpts of text citing (Clements, 1916) and it seems that this

publication is often referred to as an example of a surpassed view of succession. Therefore, this model not only lost relevance in the domain but the perspective the community had about this view also changed. Multiple applications of the PATh at different decades since the publication of Clements (1916) could reveal how this change occurred, if it was gradual or abrupt. Other thing we hypothesize that can also change with time is the difference between the model as proposed in the relevant publication and the model a community is actually using to support their studies. The propagation of misconceptions tends to increase with time (Drake et al., 2012).

Similarly, scientists at different locations of the globe may share different views about some class of phenomena (Basalla, 1967), for diverse reasons ranging from specific sociocultural aspects of a region, different commitments to ways of understanding the phenomena in different scientific communities, to diverging manifestations of the relevant phenomena at different locations. Therefore, applications of the PATh for different scientific communities, situated in different regions of the world, could show divergences in the use of models. Other factor to consider is the data basis for research. Vessuri et al. (2014) argue that big scientific databases such as Web of Science may be biased to the science made in some specific countries. Indeed, there are alternatives in some regions, such as Scielo in Latin America. This implies that research using these databases, such as ours, might be biased geographically. This raises the question of whether the application of the PATh using different databases might lead to the identification of different sets of models.

5.3. Replicability

Because the approach requires an explicit method concerning every step linking the work of scientists to the models used in a domain, the results can be subjected to criticism and re-evaluation (Drummond, 2009), which is one of the cornerstones of scientific knowledge development (Musgrave et al., 1970).

The systematic implementation of the steps of the PATh allows for a clear visualization of what the ones using the approach are proposing. Each step aims to generate results that will allow the implementation of the next step

(see Figure 1).If a critic is not able to detect flaws in any of the methodological steps, it is hard to argue that the identified models and conclusion derived from their analysis does not reflect the actual activity of the community.

On the other hand, any methodological step can be questioned if the conclusions does not seem appropriate, and this is allowed by the clear enunciation of the steps (Leydesdorff, 2001). For example, one might argue that the propositions were not adequate because the publications selected in the systematic search did not describe the activities of the community and, therefore, yielded propositions that do not contemplate adequately the models of the domain. Because the one that implemented the PATh and elaborated such propositions described each step from the definition of the domain to the propositions, any researcher can execute the exact same steps changing the parameters of the systematic search and verify if the propositions are different.

Yet another advantage that is brought by the explicitness of this approach is that it facilitates the application of an intersubjective analysis of the results. Although not entirely based on intuition, some tasks of the PATh might require some subjective decisions depending on the specific way the task is carried on. These steps could benefit from an analysis that takes into consideration the subjectivity of the proponents. Daston (1992) argues that scientists should not (and could not) achieve the elimination of subjectivity in their methodology. They should assume that subjectivity is present and pursue the use of many partial independent views to reach a conclusion that is less biased. The objective of such techniques is to develop criteria that are not based merely on the idiosyncrasy of a single researcher. Any methodological step that makes use of intuition can greatly benefit from the use of intersubjective-based techniques. There are multiple techniques to use diversity of views as a tool to reach less biased conclusions in scientific research (see Bernard and Ryan, 2009, for examples), however, these techniques are seldom used (Daston, 1992). As an example, in this application of the PATh we used an intersubjective technique to execute the task of synthesizing the excerpts of text into models, which involves classifying, generalizing and discarding data to reach a reasonable synthesis of what the community thought the model in the relevant publica-

tion was (See Supplementary Material II).

5.4. Common tool

The PATh can help increase the interest of ecologists in developing a theoretical framework aligned with actual activity, which is yet very limited in the field of ecology (Marquet et al., 2014). As a common tool that can be used for different domains and sub-domains, the PATh can facilitate communication and mutual recognition between ecologists trying to make sense of models in their own domain of expertise (Lesser et al., 2009). The demand for a theoretical organization might come from a member of the community studying the nature of a phenomenon itself. For example, a researcher could be trying to apply the PATh to the domain of landscape ecology, because this researcher self-identifies as a member of the community that studies landscape-related phenomena. In turn, there could be a researcher trying to apply the PATh to the domain of behavioural ecology, because this other researcher self-identifies as a member of the community that studies ecological phenomena related to behaviour. These two members of seemingly different communities, which studies phenomena at different scales, now are members of a third community interested in a theoretical framework based on model use and that shares a common tool. They can communicate more easily about some characteristics of each domain, such as the number and which are the most important models in each, how subdivided is the domain of study, and if they share some common models. This communication will occur more easily because each researcher understands the criteria used to reach these conclusions.

Another advantage of having the PATh as a common tool to understand the relationship between models and theoretical framework is that it may reveal new niches for research collaboration. For example, if a model is frequently used by different communities, they may be sharing an interest in the same phenomenon, or sharing the same approach to different phenomena, among other reasons (Moravcsik and Murugesan, 1975). With access to why the communities are using the same model, it may become clear how these two communities can collaborate and the interpretation and use each community

gives to the common model could reveal invaluable insights for one another.

Concluding remarks

The fact that ecologists do not use laws as guiding principles for their scientific activity, does not imply that ecology has no theory. Theories can be accessed by analysing the actual activities of scientists. While it is easy to identify logical relationships among models using a theoretical synthesis structured around laws, such synthesis are not useful to understand the actual activity of fields that develop pragmatically (Cartwright, 1997). The theoretical synthesis allowed by the PATh is mainly based on the actual activities of scientists, and therefore it reveals more about the relationship between models, phenomena and community studying the phenomena. It is important to notice that the synthesis allowed by the PATh is not prescriptive, but only descriptive. We are not stating that the identified models are the best or essential models to describe succession, we are stating that these models are frequently used to learn about the phenomenon and consequently build more knowledge about it. However, as we tried to argue, we can use the information obtained by accessing and analysing such models to make more informed decisions about what needs to change and how.

There is already a community devoted to understand what are and what role theories play in ecology (e.g. Hagen, 1989; El-Hani, 2006; Pickett et al., 2010; Scheiner and Willig, 2011; Marquet et al., 2014) and arguments that we should train more theoreticians in ecology (Rossberg et al., 2019). The data showing that the use of theory is decreasing in biology ([NRC] National Research Council, 2008) is maybe a realization that the old ways to work with theories are not enough.is maybe a realization that the old ways to work with theories are not enough. Maybe the PATh can be a new tool to deal with problems related to assuming that the generation of scientific knowledge is the combination of logical and social enterprises.

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7. References

Agazzi, E. 2004. Right, Wrong and Science: The Ethical Dimensions of the Techno-scientific Enterprise. – Rodopi.

Bailer-Jones, D. M. 1999. Tracing the Development of Models in the Philosophy of Science. – In: Magnani, L. and Casadio, C. (eds.), Model-based reasoning in scientific discovery. Springer, pp. 23–40.

Bardgett, R. D., Richter, A., Bol, R., Garnett, M. H., Bäumler, R., Xu, X., Lopez-Capel, E., Manning, D. A., Hobbs, P. J., Hartley, I. R. et al. 2007. Heterotrophic microbial communities use ancient carbon following glacial retreat. – Biology Letters 3(5): 487–490.

Basalla, G. 1967. The spread of western science. – Science 156(3775): 611–622.

Bazzaz, F. 1979. The physiological ecology of plant succession. – Annual review of Ecology and Systematics 10: 351–371.

Bernard, H. R. and Ryan, G. W. 2009. Analyzing qualitative data: Systematic approaches. – SAGE publications.

Burnham, K. P. and Anderson, D. R. 2003. Model selection and multimodel inference: a practical information-theoretic approach. – Springer Science & Business Media.

Cartwright, N. 1983. The truth doesn't explain much. – How the laws of physics lie pp. 44–53.

— 1997. Where do laws of nature come from?. – Dialectica 51(1): 65–78.

Clements, F. E. 1916. Plant succession: an analysis of the development of vegetation. – Carnegie Institution of Washington.

Colyvan, M. and Ginzburg, L. R. 2003. Laws of nature and laws of ecology. – Oikos 101(3): 649–653.

Connell, J. H. 1978. Diversity in tropical rain forests and coral reefs. – Science 199(4335): 1302–1310.

Connell, J. H. and Slatyer, R. O. 1977. Mechanisms of succession in natural communities and their role in community stability and organization. – American naturalist pp. 1119–1144.

Cowles, H. C. 1899. The Ecological Relations of the Vegetation on the Sand Dunes of Lake Michigan. Part I.-Geographical Relations of the Dune Floras.. – Botanical gazette 27(2): 95–117.

Cronin, B. 1984. The citation process: The role and significance of citations in scientific communication. – T. Graham London.

Daston, L. 1992. Objectivity and the escape from perspective. – Social studies of science 22(4): 597–618.

Drake, D., Maritz, B., Jacobs, S., Crous, C., Engelbrecht, A., Etale, A., Fourie, M., Furniss, D., Scott, S., Parusnath, S. et al. 2012. The propagation and dispersal of misinformation in ecology: Is there a relationship between citation accuracy and journal impact factor?. – Hydrobiologia pp. 1–4.

Drummond, C. 2009. Replicability is not Reproducibility: Nor is it Good Science. – In: Bottou, L. and Littman, M. (eds.), Twenty-Sixth International Conference on Machine Learning.

van Eck, N. J. and Waltman, L. 2014. CitNetExplorer: A new software tool for analyzing and visualizing citation networks. – Journal of Informetrics 8(4): 802–823.

Egler, F. E. 1954. Vegetation science concepts I. Initial floristic composition, a factor in old-field vegetation development with 2 figs.. – Vegetatio 4(6): 412–417.

El-Hani, C. N. 2006. Generalizações ecológicas. – Oecologia Brasiliensis 10(1): 3–.

Eliot, C. 2007. Method and metaphysics in Clements's and Gleason's ecological explanations. – Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences 38(1): 85–109.

Fahrig, L. 2003. Effects of habitat fragmentation on biodiversity. – Annual review of ecology, evolution, and systematics pp. 487–515.

Frankland, J. C. 1992. Mechanisms in fungal succession. – The Fungal Community: its organization and role in the ecosystem 2: 383–401.

Giere, R. N. 2010. Explaining science: A cognitive approach. – University of Chicago Press.

Grime, J. P. 1977. Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory. – American naturalist pp. 1169–1194.

Grime, J. P. 1979. Plant strategies and vegetation processes. – John Wiley & Sons, Chichester.

— 1988. The CSR model of primary plant strategies—origins, implications and tests. – In: Plant evolutionary biology. Springer, pp. 371–393.

Grubb, P. J. 1977. The maintenance of species-richness in plant communities: the importance of the regeneration niche. – Biological reviews 52(1): 107–145.

Guariguata, M. R. and Ostertag, R. 2001. Neotropical secondary forest succession: changes in structural and functional characteristics. – Forest ecology and management 148(1): 185–206.

Hagen, J. B. 1989. Research perspectives and the anomalous status of modern ecology. – Biology and Philosophy 4(4): 433–455.

Harper, J. L. 1977. Population biology of plants. – Academic Press, Cambridge.

Hubbell, S. P. 2001. The unified neutral theory of biodiversity and biogeography. – Princeton University Press, Princeton.

Huston, M. 1979. A general hypothesis of species diversity. – American naturalist pp. 81–101.

Huston, M. and Smith, T. 1987. Plant succession: life history and competition. – American Naturalist pp. 168–198.

Huston, M. A. and DeAngelis, D. L. 1994. Competition and Coexistence: The Effects of Resource Transport and Supply Rates. – The American Naturalist 144(6): 954–977.

Johnson, E. 1979. Succession an unfinished revolution. – .

Kivi, K., Kaitala, S., Kuosa, H., Kuparinen, J., Leskinen, E., Lignell, R., Marcussen, B. and Tamminen, T. 1993. Nutrient limitation and grazing control of the Baltic plankton community during annual succession. – Limnology and Oceanography 38(5): 893–905.

Kuhn, T. S. 2012. The Structure of Scientific Revolutions: 50th Anniversary Edition. – University of Chicago Press.

Latour, B. 2005. Reassembling the social: An introduction to actor-network-theory. – Oxford University Press.

Lawton, J. H. 1999. Are there general laws in ecology?. – Oikos pp. 177–192.

Lesser, E., Fontaine, M. and Slusher, J. 2009. Knowledge and communities. – Routledge.

Leydesdorff, L. 2001. The challenge of scientometrics: The development, measurement, and self-organization of scientific communications. – Universal-Publishers.

MacArthur, R. H. and Wilson, E. O. 1963. An equilibrium theory of insular zoogeography. – Evolution pp. 373–387.

Marquet, P. A., Allen, A. P., Brown, J. H., Dunne, J. A., Enquist, B. J., Gillooly, J. F., Gowaty, P. A., Green, J. L., Harte, J., Hubbell, S. P. and others 2014. On theory in ecology. – BioScience 64(8): 701–710.

McCune, B., Grace, J. B. and Urban, D. L. 2002. Analysis of ecological communities. – vol. 28. MjM software design Gleneden Beach, OR.

McGrath, M. 2014. Propositions. – In: Zalta, E. N. (ed.), The Stanford Encyclopedia of Philosophy. Stanfor University. Spring 2014 ed.

McIntosh, R. P. 1986. The Background of Ecology: Concept and Theory. – Cambridge University Press.

McIntosh, R. P. 1999. The succession of succession: a lexical chronology. – Bulletin of the Ecological Society of America 80(4): 256–265.

Moravcsik, M. J. and Murugesan, P. 1975. Some results on the function and quality of citations. – Social studies of science 5(1): 86–92.

Morgan, M. S. and Morrison, M. 1999. Models as Mediators: Perspectives on Natural and Social Science. – Cambridge University Press.

Mukherjee, S., Romero, D. M., Jones, B. and Uzzi, B. 2017. The nearly universal link between the age of past knowledge and tomorrow's breakthroughs in science and technology: The hotspot. – Science advances 3(4): e1601315.

Musgrave, A. et al. 1970. Criticism and the Growth of Knowledge: Volume 4: Proceedings of the International Colloquium in the Philosophy of Science, London, 1965. – vol. 4. Cambridge University Press.

Myster, R. and Pickett, S. 1988. Individualistic patterns of annuals and biennials in early successional oldfields. – Plant Ecology 78(1): 53–60.

Noble, I. R. and Slatyer, R. 1980. The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbances. – Vegetatio 43(1-2): 5–21.

[NRC] National Research Council 2008. The role of theory in advancing 21st-century biology: catalyzing transformative research. – National Academies Press.

Odenbaugh, J. 2005. Idealized, inaccurate but successful: A pragmatic approach to evaluating models in theoretical ecology. – Biology and Philosophy 20(2-3): 231–255.

Odum, E. P. 1969. The strategy of ecosystem development. – Sustainability: Sustainability 164: 58.

O'Hara, R. 2005. The anarchist's guide to ecological theory. Or, we don't need no stinkin'laws. – Oikos 110(2): 390–393.

Pickett, S., Collins, S. and Armesto, J. 1987. Models, mechanisms and pathways of succession. – The Botanical Review 53(3): 335–371.

Pickett, S. and White, P. 1985. The ecology of natural disturbance and patch dynamics. – Academic Press, San Diego.

Pickett, S. T., Cadenasso, M. L. and Meiners, S. J. 2005. Vegetation dynamics. – Vegetation ecology pp. 172–198.

Pickett, S. T. A., Kolasa, J. and Jones, C. G. 2010. Ecological Understanding: The Nature of Theory and the Theory of Nature. – Academic Press.

Pickett, S. T. A., Meiners, S. J. and Cadenasso, M. L. 2011. Domain and Propositions of Succession Theory. – In: Scheiner, S. M. and Willig, M. R. (eds.), The theory of ecology. Chicago.

R Development Core Team 2008. R: A Language and Environment for Statistical Computing. – R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0.

Rosenberg, A. 1985. The Structure of Biological Science. – Cambridge University Press.

Rossberg, A. G., Barabás, G., Possingham, H. P., Pascual, M., Marquet, P. A., Hui, C., Evans, M. R. and Meszéna, G. 2019. Let's Train More Theoretical Ecologists–Here Is Why. – Trends in ecology & evolution .

Saunders, D. A., Hobbs, R. J. and Margules, C. R. 1991. Biological consequences of ecosystem fragmentation: a review. – Conservation biology pp. 18–32.

Scheiner, S. M. and Willig, M. R. 2011. The Theory of Ecology. – University of Chicago Press.

Shelford, V. E. 1911. Ecological succession: 1. Stream fishes and the method of physiographic analysis. – The Biological Bulletin 21(1): 9–35.

Shugart, H. H. et al. 1984. A theory of forest dynamics. The ecological implications of forest succession models.. – Springer-Verlag.

Smart, J. J. C. 1968. Between science and philosophy. – Random House.

Sneath, P. H., Sokal, R. R. et al. 1973. Numerical taxonomy. The principles and practice of numerical classification.. – W.H. Freeman and Company.

Swoyer, C. 1991. Structural Representation and Surrogative Reasoning. – Synthese 87(3): 449–508.

Tilman, D. 1985. The resource-ratio hypothesis of plant succession. – American Naturalist pp. 827–852.

— 1987. Secondary succession and the pattern of plant dominance along experimental nitrogen gradients. – Ecological monographs 57(3): 189–214.

Tilman, D. 1988. Plant strategies and the dynamics and structure of plant communities. – Princeton University Press.

Turchin, P. 2003. Complex population dynamics: a theoretical/empirical synthesis. – vol. 35. Princeton university press.

Vessuri, H., Guédon, J.-C. and Cetto, A. M. 2014. Excellence or quality? Impact of the current competition regime on science and scientific publishing in Latin America and its implications for development. – Current sociology 62(5): 647–665.

Von Bertalanffy, L. 1973. The meaning of general system theory. – General system theory: Foundations, development, applications pp. 30–53.

Watt, A. S. 1947. Pattern and process in the plant community. – Journal of ecology 35(1/2): 1–22.

Wieczorek, S. K. and Todd, C. D. 1998. Inhibition and facilitation of settlement of epifaunal marine invertebrate larvae by microbial biofilm cues. – Biofouling 12(1-3): 81–118.

Winther, R. G. 2006. Parts and theories in compositional biology. – Biology and Philosophy 21(4): 471–499.

— 2016. The Structure of Scientific Theories. – In: Zalta, E. N. (ed.), The Stanford Encyclopedia of Philosophy. Metaphysics Research Lab, Stanford University. Winter 2016 ed.

Woodward, J. 2019. Causal Complexity, Conditional Independence and Downward Causation. – This paper is forthcoming in PSA 2018.

Zar, J. H. et al. 1999. Biostatistical analysis. – Pearson Education India.