Identifying models of a pragmatic theory of ecology

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Abstract

Ecology has suffered criticisms related to its theoretical development, in particular, that ecology does not have a unified explicit theory. However, the pragmatic view of science – a strand of the most commonly held view of science among philosophers of science (semantic view), assumes that the theory is an aspect of the activities of scientists and should not necessarily be explicit to guide the generation of knowledge. Under the pragmatic view, a theory is a family of models and the its formalization consists of the organization of these models and the principles guiding models' conception. Here we present an analysis to identify which are the most relevant models within a domain of study and how these models are being referred as the conceptual basis of new models. We argue that a domain of study can be delimited around a community studying a specific class of phenomenon. The study of a class of phenomenon corresponds to the construction of models of the phenomenon that are based on previously proposed models. By accessing how the most referred models are cited in the literature, we are able to identify the most used models of the domain. The proposed analysis can be described as the following steps: (1) the definition of the domain of study, (2) the identification of scientific activities within the domain, (3) the identification of most relevant publications within the domain, (4) the identification of most relevant models within relevant publications. We also present the results of the first imple-

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mentation of the proposed approach and discuss its technical implications and benefits. We conclude that the use of the proposed approach is effective in the process of organizing a pragmatic theory. The analysis has the potential to become a common tool shared by scientists interested in organizing models of different domains. That should connect more scientists around questions related to theory structure in ecology.

Keywords:

theory structure, pragmatic view, semantic view, model definition,

philosophy of ecology, method development

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1. Introduction

Ecology is considered a single domain of study, which has its own professional societies and specialized journals(Hagen, 1989), indicating an acceptance that ecologists are working to generate knowledge about a specific class of phenomena (Broszkiewicz, 2013). Given this acceptance, there are several reasons to dedicate time and resources to formalize a theoretical framework making explicit the propositions that unify models within this domain of study. By doing so, the knowledge generated in each sub-domain can be compared for concordances, inconsistencies, and to identify knowledge gaps, and methods can be evaluated and perfected for many intended purposes (Scheiner and Willig, 2008; Pickett et al., 2010; Kolasa, 2011; Odenbaugh, 2011). For example, formalizing a theoretical framework would avoid spurious discussions about different phenomena that receive similar names or prevent that the same phenomena are treated as more than one. A theoretical disunity within a scientific community is characterized by three aspects: (I) generation of dissociated knowledge, which ensures large conceptual gaps among sub-disciplines, (II) many specific models and few general models, and (III) the creation and maintenance of isolated communities that have their own concepts, models, and theories, further promoting disunity (Pickett et al., 2010). Hence, put together these three aspects might push a domain into a vicious cycle of disunity.

Gaps of knowledge among different sub-domains are usually difficult to identify and fill because few members of isolated communities are willing to learn the concepts, methods, models and theories of other communities (Keller, 2009; Lesser et al., 2009; Kuhn, 2012). This precludes the flux of knowledge among sub-domains, making evermore difficult to conceive unified general models, and the sub-domains develop increasingly apart. If ecology has unifying propositions that can be organized in a theoretical framework – as proposed by some authors (Lawton, 1999; Weber, 1999; Colyvan and Ginzburg, 2003; El-Hani, 2006; Scheiner and Willig, 2008; Pickett et al., 2010) –, organizing and making these concepts explicit would help ecologists to identify agreements, disagreements, gaps of knowledge, and avoiding spurious discussion.

The identification and organization of propositions into a coherent framework might be considered the organization of a theory itself (Suppe, 2000). The search for widely recognized propositions within the ecological domain is not, however, the search for laws. Most discussions about the organization of theories in ecology turned into debates about the existence and relevance of laws in ecology (O'Hara, 2005; Gorelick, 2011; Rosenberg, 1985; Hagen, 1989). "Laws" can be defined as universal statements described in first-order logic that orient the development of new statements by formal deduction (Suppes, 1961). Authors that investigated the existence of universal laws of ecology reached the conclusion that ecology does have some widely accepted propositions about the natural world (Weber, 1999; Kolasa, 2011; Colyvan and Ginzburg, 2003; Lawton, 1999). However, these largely accepted propositions were not assumed to be universal and were seldom expressed in first-order logic. Therefore, these propositions were not considered laws of ecology, but they were indeed considered relevant to the theoretical development of ecology (El-Hani, 2006).

The assertion that ecology has widely recognized propositions relevant to its theoretical development, implies that these propositions are being used to further generation of knowledge within this domain of study (El-Hani, 2006). These widely accepted propositions work as the conceptual basis to formulate new propositions about the natural world, assuming a role very similar to laws in views of theories based on laws (Suppe, 1989). If some set of propositions is widely recognized by a community studying a phenomenon as the conceptual basis of their activity, making these propositions explicit can be viewed as the formalization of the theory of this phenomenon (Suppe, 2000). The use of semantical propositions to structure a theory is currently the most commonly held philosophical analysis of the nature of theories. This view is known as the "semantic view" of theories (Van Fraassen, 1986; Suppe, 1989; Castle, 2001). To formalize a set of propositions is to describe these propositions in some specific language. When one describes a proposition into a specific language these propositions can be communicated and manipulated. The description of propositions in a specific language is what we will refer from here forth as "model". Some authors argue that in the semantic view, theories are families of models about a determined class of phenomena (Castle, 2001; Morgan and Morrison, 1999; Suppe, 2000).

Models can vary greatly in level of generality (Morgan and Morrison, 1999). There are models that describe general aspects of a phenomenon and there are models that describe specific properties of phenomenon allowing for clear manipulation and generation of a hypothesis. Usually, there are many propositions about a phenomenon that are described in very specific models, in these cases, it becomes impractical to formalize a theory listing all models made about the phenomenon. The formalization of theory, however, can be done by describing the general models that unify the more specific models within this domain (Scheiner and Willig, 2011). The manipulation of models leads to a better understanding of these models, and knowledge about the models can be interpreted as knowledge about the natural phenomena (Swoyer, 1991).

The formalization of a theory of a phenomenon can be made prior to the conception of the models within the domain. One could try to conceive a set of fundamental propositions within a domain of study and create models from these set of propositions. However, it has been argued that ecology already has widely accepted generalizations about the natural world (El-Hani, 2006), what indicates that ecology already has a set of propositions used to conceive models of the ecological phenomenon. These propositions are the basis of many models described in the literature. Therefore, if we want to formalize a theory of ecology using the knowledge that already exists, it seems reasonable to look for the propositions that are already being used to conceive models.

An explicit structure for the theory of ecology, aligned with the semantic view of theory, has already been proposed. In 2005, Samuel Scheiner and Michael Willig published an article in which they describe "the theory of gradients" (Scheiner and Willig, 2005), a constitutive theory within the domain of ecology. Subsequently, they proposed "a general theory of ecology" (Scheiner and Willig, 2008), which they developed exemplifying constitutive theories in the book "The theory of ecology", (Scheiner and Willig, 2011). The proposed theory was presented as a hierarchy with three levels. At the highest level lies the general theory, which is composed, at an intermediate level, by constitutive theories, in turn containing, at the lowest level, one or more models. Scheiner and Willig's general theory of ecology is structured by propositions that, accordingly to the authors, are recognized by ecologists since the 19th century and were largely accepted by the community since the 1950s. Therefore they tried to identify propositions of a theory of ecology that already existed but were not formalized. The propositions were reached based on what experts in each sub-domain thought were the propositions of their respective domain. These experts were requested to link these propositions with the most relevant models and the general principles of ecology (conceived by Scheiner and Willig themselves). This way the hierarchical framework was ensured. Although Scheiner and Willig's proposed framework seems promising to help ecologists to recognize the underlying theoretical structure of their practice, there is no explicit method to supporting the idea that those propositions actually unify the models in use by ecologists in each sub-domain.

Here, we propose an approach to identify the most important models within a particular domain or sub-domain of study. Here we detail the conceptual basis of the approach and its assumptions. We then provide a worked example of the application the approach to the domain of ecological succession. We describe, then, the specific methodological decisions we made to implement the approach and the results observed. We end up discussing the benefits of using it to organize propositions and models.

2. PATh - Pragmatic Approach to Theories

The approach we are proposing assumes that theories in ecology are made in a pragmatic way. The pragmatic view of theories is a strand of the semantic view and, therefore, continues to consider theories as a family of models (Winther, 2016). However, under the pragmatic view, the theory is a reflex of the activities in a domain. A pragmatic view is opposed to an axiomatic view of theory. In the axiomatic view, the theory is first proposed as a set of fundamental principles, and models are conceived as derivations from these fundamental principles (Suppe, 2000). In the pragmatic view, the theory of a phenomenon is an elusive entity that exists in the set of models used by the community to represent the phenomenon (Giere, 2010). This set of models is constantly changing as the models are being combined, re-conceived, and re-purposed. Because changes in the set of models also change the theory, some authors argue that it is impractical to formalize a pragmatic theory. However, we are proposing that it is possible to assess moments of a pragmatic theory development.

The set of models representing a phenomenon are not equally recognized within a community. Some models are frequently referred by the community others are mostly ignored. The status of a model might change with time, location and community studying the phenomenon. We propose that as some models become more frequently used to generate new models, this model become more relevant to the community. Therefore, the propositions that support these models are widely recognized within a domain.

We are stating that, within ecology, domains have a set of unifying propositions and that we can identify and organize these propositions by looking into how models are being used in this domain. If the set of unifying propositions and models can be considered the theory of this domain (Suppe, 2000), we can state that the theory of ecology already exists and only needs to be made explicit. This assumption is essentially pragmatic. Thus the approach we are proposing to organize the theory of ecology is a Pragmatic Approach to Theories – PATh.

The assumption that models are entities that connect via information flux is aligned with the systemic view of science. Therefore, the PATh assumes that science works as a system (*sensu* Von Bertalanffy, 1973), which means that scientific activity works as 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 details of the dynamics of science systems, provided that such dynamics includes the use of models. Given our assumption that models are at the basis of theories (Scheiner and Willig, 2011), in the pragmatic view, the theory is built as models are developed and negotiated in a social system, which in turn creates a directed network of affiliations of models and scientists (sensu Otte and Rousseau, 2002). Assessing properties of this network should give insights on how information circulates within a community, and which information is most important for model conception within this domain.

The network of affiliations among scientists and models can be tracked in the citation network of scientific texts. Such documents have a central role in the accreditation of the results of scientific work that is negotiated in the science social system (Cronin, 1984; Latour and Woolgar, 2013). Citing is a key piece of this negotiation and a complex process with many social, cultural and subjective causes (Cronin, 1984; Zhang et al., 2013). Nevertheless, we assume that one of the motivations behind citing is to propose conceptual links among scientific texts. In our view, such links are interpretations of a model by citing authors that is, the meaning that citing authors create for a given model in order to use it (Small, 1978). In doing so, citing authors make a network of citations that informs not only about which models are central to a given domain. By examining the content of the citations we can also assess how and why models are being used. Hence we propose that a content analysis of the citation network informs how theory is built up by the development, interpretation and exchange of models by scientists.

In synthesis, the approach we are proposing consists of defining a domain of study for which one intends to understand the theoretical structure, identifying the scientific activities within this domain of study, and then identifying the most relevant models within the domain. We think the PATh can be methodologically implemented in more than one way. We already implemented the PATh to one domain of study and reached the conclusion that the approach is executable and useful to understand the theoretical structure of a domain. In the next section, we present the way we implemented it and justify the decisions we made to execute each methodological step.

3. The Implementation of the PATh

In the process of implementing the PATh, we made several methodological decisions. We tried to make decisions aligned with the premises of the approach, however, we realize that some of these methodological decisions were operational only. Therefore, these decisions can be changed if necessary without changing the nature of the approach. Here, we described in details all the methodological steps we took to go from the definition of the domain of study to the most relevant models in use within the domain.

3.1. Definition of domain

As discussed, the theory can be interpreted as the views of a community about a class of phenomenon. Therefore, the definition of a domain of study is not only the definition of a class of phenomenon but it also includes the definition of the community studying the phenomenon. Because different communities can have different views about the class of phenomenon, the definition of the domain is the definition of a class of phenomenon as viewed by a defined community.

We defined the phenomenon of interest as ecological succession. Within ecology, this definition of the phenomenon of interest seems to be unambiguous enough to lead to a cohesive community. We realize that most domains would have to have a more detailed definition of the class of phenomena. We decided to define the community studying ecological succession as those who self-identified as researchers of ecological succession. As a first implementation of the PATh, we defined that we would analyze the current view about ecological succession, i.e. the activity of the community of the last 10 years. As a first implementation, we wanted to analyze only those views about successional processes that were related to other ecological processes. We, therefore, decided to restrict our analysis to activities entitled by their authors as ecological studies.

Results:. As the result from the first step we defined the phenomenon of interest – ecological succession. We defined the scope in time for which we want to identify the models of succession – the last 10 years. We defined that this community must identify itself as doing research with ecological succession.

3.2. Identifications of scientific activities of the domain

To identify the activities of the community studying ecological succession in the last 10 years, we searched for publications containing the keyword "succession" in the title or abstract. This search was conducted in the Web of Science database (July 15th, 2017), in the "Ecology" category. In the actual search, we used the terms "successi*" in the "Topic" field.

Because "succession" is a term relatively unambiguous (McIntosh, 1986) within ecology, we expected that the majority of the publications, in fact, were referring to succession as defined by Pickett et al. (2011) and our expectations were met. Furthermore, because the publications identified in this step were not analyzed by their content, the inclusion of publications that do not refer to ecological succession has no effect. These publications were used to identify the most cited publications in the next step. Therefore these first identified publications need to be a good representation of what is being discussed in the community but does not need to contemplate exactly all that is being discussed.

It is important to note that the systematic search is not the only way to identify the activities of the community studying a phenomenon. However, the systematic search is a particularly known technique that has several already available tools and can be easily communicated among researchers.

Results:. This search resulted in 5,536 publications, dating from the year 2007 to 2017, in the category "Ecology" of Web of Science.

3.3. Identification of most relevant publications

The publications identified in the previous step allowed us to understand which are the most relevant publications. We considered that the more a publication is cited by the community the more relevant it is to build knowledge in the domain. To identify the most cited publications, we created a network including the 5,536 publications identified in the second step and the publications cited by these first publications (predecessors) by using the program CitNetEplorer (van Eck and Waltman, 2014). It is important to note that the starting publications were dated from 2007 to 2017 but the predecessors-publications could be from any year. This means that we are interested in finding which are the most important models for the studies of the last ten years, regardless of the publication year.

The criterion for selection of the most relevant publications of the network among all publications was saturation of successors within the network. The saturation of successors was reached as follows. We dubbed the publication that had the highest citation index of the entire network (including publications from all years) as "relevant publication" and checked the successors (citing publications) that only could come from the network of publications of the last 10 years (5,536 publications). Then we checked the percentage of this network that was composed by the successors of the publications with the highest citation index. If 100% of the network from the last ten years was not reached, we would add the second most cited publications to the list of relevant publications and check if the successors of the most cited publication and the second most cited publication composed 100% of the network of the last ten years. We repeat the process summing the successors of the first 100 most cited publications. However, all successors of the first 100 most cited publications did not compose 100% of the network of the last 10 years. After adding 25 most cited publications to the list of "relevant publications", adding new publications did not seem to cause an increase in the percentage of successors composing the network of the last 10 years. We made this test including only direct successors, including direct and 2nd-degree successors, and including direct, 2nd and 3rd degree successors and in all cases, there seems to be an asymptote with around 25 relevant publications (Figure 1). The asymptote is about 80% of the network when the successors from the 25 most cited publications accumulate if we consider the direct and 2nd-degree successors. We adopted these 25 most cited publications as the central ones for the activity of the researchers of the domain.

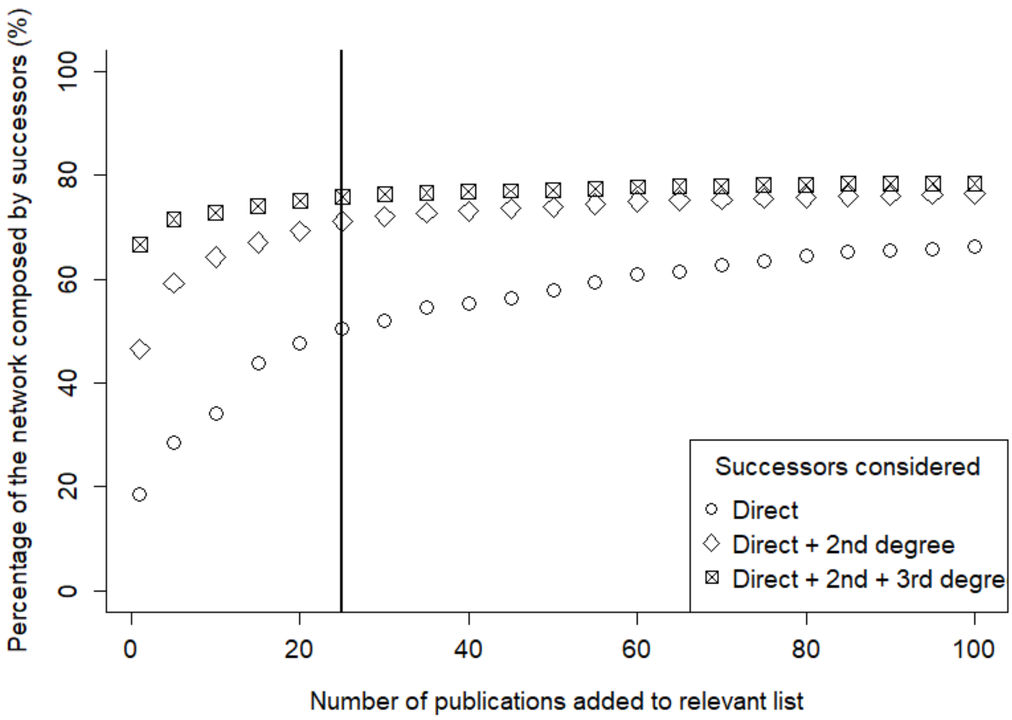

Figure 1: Comparison between lines of saturation of the percentage of the network composed by the successors of most cited publications of the network. The "Y" axis shows the proportion of the entire network generated by the third step of the PATh that is composed by successors of the publications included in the relevant list. The "X" axis shows the size of the relevant publications list.

278 *Results:.* List of the most cited publications within the domain – Table 1.

Table 1: List of relevant publications sorted by number of citations

Titke	**Number of citations**
CONNELL, J. H. & SLATYER, R. O. 1977. Mechanisms of succession in natural communities and their role in community stability and organization. American naturalist 1119–1144.	780
GRIME, J. P. 1979. Plant strategies and vegetation processes. John Wiley & Sons, Chichester.	468
CONNELL, J. H. 1978. Diversity in tropical rain forests and coral reefs. Science 199:1302–1310.	400
HARPER, J. L. 1977. Population biology of plants. Academic Press, Cambridge.	374
ODUM, E. P. 1969. The strategy of ecosystem development. Sustainability: Sustainability 164:58.	343
PICKETT, S. & WHITE, P. 1985. The ecology of natural disturbance and patch dynamics. Academic Press, San Diego.	306
GRUBB, P. J. 1977. The maintenance of species-richness in plant communities: the importance of the regeneration niche. Biological reviews 52:107–145.	294
TILMAN, D. 1988. Plant strategies and the dynamics and structure of plant communities. Princeton University Press.	285
EGLER, F. E. 1954. Vegetation science concepts i. initial floristic composition, a factor in old-field vegetation development with 2 figs. Vegetatio 4:412–417.	279
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 27:95–117.	271
MACARTHUR, R. H. & WILSON, E. O. 1963. An equilibrium theory of insular zoogeography. Evolution 373–387.	266
BAZZAZ, F. 1979. The physiological ecology of plant succession. Annual review of Ecology and Systematics 10:351–371.	215
HUSTON, M. 1979. A general hypothesis of species diversity. American naturalist 81–101.	203
HUSTON, M. & SMITH, T. 1987. Plant succession: life history and competition. American Naturalist 168–198.	200
GRIME, J. P. 1977. Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory. American naturalist 1169–1194.	198
HUBBELL, S. P. 2001. The unified neutral theory of biodiversity and biogeography. Princeton University Press, Princeton	189
PICKETT, S., COLLINS, S. & ARMESTO, J. 1987. Models, mechanisms and pathways of succession. The Botanical Review 53:335–371.	183
WATT, A. S. 1947. Pattern and process in the plant community. Journal of ecology 35:1–22.	178
TILMAN, D. 1987. Secondary succession and the pattern of plant dominance along experimental nitrogen gradients. Ecological monographs 57:189–214.	178
HUSTON, M. A. & DEANGELIS, D. L. 1994. Competition and Coexistence: The Effects of Resource Transport and Supply Rates. The American Naturalist 144:954–977.	177
GRIME, J. P. 1988. The csr model of primary plant strategies—origins, implications and tests. Teoksessa Plant evolutionary biology, 371–393. Springer.	176
NOBLE, I. R. & SLATYER, R. 1980. The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbances. Vegetatio 43:5–21.	171
TILMAN, D. 1985. The resource-ratio hypothesis of plant succession. American Naturalist 827–852.	163
SHUGART, H. H. ET AL 1984. A theory of forest dynamics. The ecological implications of forest succession models. Springer-Verlag.	160
SOUSA, W. P. 1984. The role of disturbance in natural communities. Annual review of ecology and systematics 15:353–391.	160

3.4. Identification of models described in the relevant publications

To identify the "models in use" within each relevant publication we used two methods. First, for each relevant publication, we separated the successor publications and organized them also by the number of citation. Then we searched in the publications of this list for the excerpts of text in which the focal relevant publication was cited. We then separated 50 excerpts of text in which only the relevant publication was cited. This number of text excerpts was chosen because it was reported in a pilot test that this number was enough to proceed to the next method of the step. In the second method of this step, all 50 excerpts of text citing each relevant publication were synthesized in one or more verbal models. To synthesize the models, we used a technique that considers the subjectivity of the process by consulting more than one individual. Each set of 50 excerpts of text citing each relevant publication was analyzed in respect to its similarities and differences by a group of three people. Each person was oriented to create a synthesis of what they thought was the most important model of the natural world described in the relevant publication based on her or his reading of the 50 excerpts of text citing the relevant publication. Each individual synthesis was presented to the group. The trio then participated in a consensus activity adapted from the "Nominal Group Technique (NGT)" (Bernard and Ryan, 2009).

The application of the adapted NGT proceeded as follows:

1. The proposed synthesis of each person of the trio was presented to the entire trio, without each person knowing the authors of the synthesis, except their own proposed synthesis. The proposed synthesis was the description of how many and which were the most relevant models described in the focal relevant publication. Each model is then numbered.
2. After reading the proposition of their peers, each person in the trio reevaluates their own proposed synthesis and make a new proposal. This new proposal is solely the combination of which of the numbered models should be used to synthesize the relevant models of the focal relevant publication. The participants in the activity should consider that some

of the models presented in the first round might be combined in a single model, others might be kept separated (if one thinks the literature is referring to more than one model in this publication), and other might be discarded as non-relevant mention in the literature.

3. The combination proposals are then presented to the trio, again without each person knowing the author of each combination proposal, except by their own.
4. The combination proposals are then ranked by the participants in a scale from the most adequate to least adequate according to their individual views. The combination proposal with the higher rank considering the ranking of all three participants is selected. If the combination proposal states that the literature refers to the focal relevant publication by more than one model, the next rounds are applied to each individual model.
5. The model or models are selected to be synthesized textually for each one of the participants individually. This time the participants should consider only the models numbered in the first round.
6. For each model re-synthesized, the three synthesis made for each participant are presented, again without each person knowing the authors of each synthesis. Then, the newly proposed synthesis are ranked as in the previous round and the synthesis with the higher rank is selected.
7. The selected synthesis is submitted to an open evaluation by the participants that propose modifications to it if they think necessary. The modifications are compared to the synthesis selected in the 6^{th} turn and re-ranked.
8. The process described in the turn 6 and 7 are repeated until consensus is reached.

Results:. For the 25 relevant publications we synthesized 30 textual models describing the natural world.

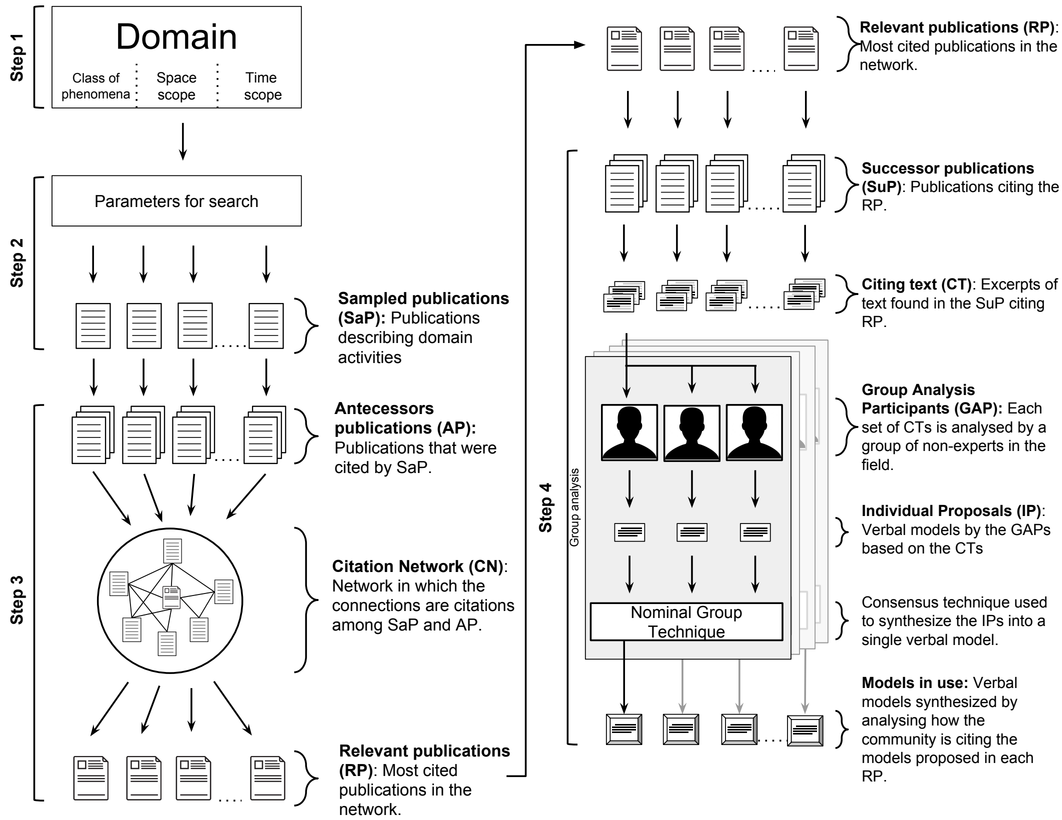

Figure 2: Workflow of our approach to identify the theoretical structure of a scientific domain from the models cited in the publications of the domain. Although the AboUT is divided into steps, the whole process is a continuum of data obtaining and usage to access new information about the domain.The last elements within each step is what we described as the result of the step.

4. Understanding the domain through the resulting models

The resulting models are a textual description of the natural world. These models were used as evidence of the The 30 models resulting from the step 4 of the PATh are listed in the supplementary material. Based on the description of the 30 models we were able to identify patterns of use of models and suggest unifying propositions for the domain. These patterns gave us novel insights on the actual views of the community studying ecological succession. First, we noted that 6 of the 30 identified models of the domain did not include the word "succession" in its description. These models describe mechanisms related to the effects of disturbance (model 4 - RP by Connell (1978); model 16 - Huston (1979)), the effect of dispersal range and colonization probability (model 14 - RP by MacArthur and Wilson (1963); model 19 - RP by Hubbell (2001)), and often mechanisms related to nutrient partition (model 22 - RP by Watt (1947)). Even though the cited relevant publications do not focus on describing or explaining the phenomenon of succession, they apparently describe important concepts that are currently being used to build new models of succession. For example, the domain of succession for many years was based soundly on niche theory (Pickett et al., 2010), however, the members of the community today do consider insights presented in Hubbell's neutral theory. One prerogative of the PATh is that it allows us to check how and understand why a publication is being frequently cited in a domain by accessing the excerpts of text. The neutral model is frequently used to explain successional patterns at landscape scales 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. Second, we noted a change across time in the views of the actor of succession in the domain. For example, the "modern" view of succession (sensu Pickett et al., 2011) adopts a more individualistic approach, in which the actors of succession are the individuals (Gleasonian view) rather than the communities (Clementisian view) (Clementisian view) (Myster and Pickett, 1988). However, the high frequency of citation of models considering supra-individual entities as the actors of succession (model 6 - RP by (Odum, 1969); model 30 - RP by (Guariguata and Ostertag, 2001)), shows that the "modern" view has not been completely acknowledged by the community studying succession at the present. Furthermore, Odum's seminal article is among the 5th most cited publication in a network of more than five thousand publications. Hence, there is little doubt that the community studying succession still adopts the supra-individual approaches to succession as a possible way to understand the phenomenon.

By comparing models, we were able to elaborate a set of propositions unifying the 30 identified models. These propositions were elaborated based on two criteria: i) the propositions should contemplate all 30 models, ii) any model that assume these propositions as true will be considered models of the class of phenomena delimited in the domain. The criteria are aligned with the definition of structuring propositions as defined by Suppe (2000). The three propositions unifying all models can be described as follows:

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 : The species have different probabilities of taking a fraction of the total resource units that become available. This difference can be due to (a) different probabilities of colonization; (b) different probabilities of individuals at the site or their propagules of taking resource units.

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.

This set of propositions that unify the identified models advances our understanding of the theory behind the practice of the community studying ecological succession. They can be viewed as basic principles of the theory of ecological succession. Even though the models themselves, most certainly, were not conceived with these principles in sight, by adopting these propositions as true one could have conceived these models. This means that any model that assume these propositions as true is akin to the identified models and should be considered as a model within the domain of ecological succession.

5. Benefits of the PATh

5.1. Set theoretic analysis of theory structure

The PATh can be used to understand how models are being used within a domain. This analysis should allow for a better understanding of how different domains overlap, or whether the focal domain has sub-domains or is entirely encompassed by a broader recognized domain.

Scheiner and Willig (2011) proposed a hierarchical framework in which general theories encompasses different constitutive theories, which in turn encompasses models. They stated that is just a hypothetical framework and that theories often overlap. What we observed, in the domain of ecological succession we used to test the PATh, is that some of the models that are used frequently come from publications that are among the most cited of whole ecology domain (MacArthur and Wilson, 1963; Hubbell, 1997; Odum, 1969; Tilman, 1985). It would not be surprising if these publications are relevant publications in other domains seemly 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 constitutive theories that have something in common or that both models pertain to some general theory. For example, some propositions structuring the model of island biogeography are also used to structure models of succession. However, it seems that these same propositions are particularly important to phenomena related to habitat fragmentation (Saunders et al., 1991; Fahrig, 2003). Therefore, the domain of ecological succession and landscape ecology overlap in some aspects. This indicates that either there are researchers that are part of both communities or there are two different communities that share some views about the natural world.

Another scenario that the PATh allows us to detect is the existence of sub-domains within the focal domain. Pickett et al. (2011) stated that in the modern view of succession the actors of the succession are individuals. Most of the models resulting from the application of the PATh are models about the interaction of individuals, in fact. However, some of the resulting models clearly described succession as a process that can happen at supra-individual levels (Model 6 - RP by Odum (1969); Model 30 - RP by Guariguata and Ostertag (2001)). This might indicate that the community is divided into those who assume the individualistic view of succession, and those that assume that succession is not an individualistic process intrinsically, and it can be viewed as a process happening at the community level. The propositions elaborated by us can be assumed by both groups; however, the first group is restricted to a more specific domain of study, one for which changes in the community can only be caused by interactions between individuals. In this case, one could add a new excluding proposition stating that "changes in the community are caused by the interactions of individuals".

Divergences within a domain might be an indication of gaps in knowledge.

In the example given a lingering question is "why some ecologists think succession is a process resulting exclusively from interactions among individuals?". If this view is supported by empirical data, "why there are some ecologists who think succession is a process that might be caused by supra-individual mechanisms?". Is the theory of succession requiring a conceptual cleaning? Or is it requiring more empirical data? All these questions are now justified based on the results of the application of the PATh.

5.2. Historical and geographical analysis of theories

The definition of the domain implies the definition not only of the class of phenomena but the scope in space and time. These parameters of the analysis are important because the views about a class of phenomena might change from time to time and place to place (Kuhn, 2012). Multiple applications of the PATh can be used to assess these changes.

Because it takes time for a model to be analyzed and widely recognized by the community, a model presented this year has little chance to be as frequently referred 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 to a given time frame. The application of the PATh at different time frames through history will show exactly which models are the most used through time. Moreover, it can show how the models in use change in relation to the proposed models. For example, in the first implementation of the PATh, we detected that the publication by Clements (1916) was among the 50 most cited. However, this publication is often referred to as an example of a surpassed view of succession. Therefore, it is not being cited for its proposed model, but rather for its historical relevance. Multiple applications of the PATh at different decades since this publication by Clements (1916) could reveal how this paradigmatic changed occurred.

Similarly, scientists at different locations of the globe might share different views about some class of phenomena (Basalla, 1967), because phenomena might manifest differently at different locations. Therefore applications of the

PATh for different geographical communities in the world could show divergences in the use of models.

5.3. Replicability

Because the approach require an explicit method about every step linking the work of scientists to the presented models of the theory, the results are subjected to criticism and re-evaluation (Drummond, 2009), which is one of the cornerstones of scientific knowledge development (Musgrave et al., 1970). The description of the application of the PATh step by step can be viewed as the presentation of a logical argument which the conclusion is that the unifying propositions contemplate the views of the community. The first premise is that the selected publications of the literature describe the relevant activities of the domain. The second premise is that the selected most cited publications are the most relevant publications of the domain. The third premise is that the set of final propositions contemplate all the models of the domain. If these three premises are true, then it is reasonable to conclude that the unifying propositions reflect the pragmatic theory of the domain.

As in any argument, the premises can be confronted when a conclusion does not seem appropriate (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 proponent of the theory described each step from the definition of the domain to the propositions, any researcher can verify that statement of the opponent by executing the exact same steps and changing the parameters of the systematic search. Yet another advantage that is brought by the explicitness of this approach is that it facilitates the application of an inter-subjective analysis of the results. 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. An analysis that uses this approach is subjected to *aperspectival objectivity*. There are tools developed to submit data to systematic group analysis (Bernard and Ryan, 2009). The objective of these tools is to develop criteria that are not based merely on the idiosyncrasy of a single researcher. 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 proponents. For example, the task of synthesizing the excerpts of text into "models in use". This task involves classifying, generalizing and discarding data to reach a reasonable synthesis of what the community thought the model in the relevant publication was. This task can greatly benefit from systematic group analysis (Bernard and Ryan, 2009).

Because the approach requires an implementation divided into steps with clear expected results, we can better judge if the result is adequate to the objective we are trying to reach. This allows for a more clear decision on what can be done to increase the confidence in each result and, therefore, in the final result: the theory structure.

5.4. General tool

The study of theory structure and development in ecology is yet a small area within ecological studies (Marquet et al., 2014). For a more efficient resolution of the questions about theory development in ecology, it is necessary to have more ecologists interested in theory structure and development. The PATh can help increase the interest of ecologists in theory structuring.

As a general tool that can be used for different domains and sub-domains, the PATh should facilitate communication and mutual recognition between ecologists trying to organize 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. On the other hand, 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 phenomena related to behaviour in ecology. These two members of seemly different communities, that operate on very different scales, now are members of a third community interested in theory structure and that share a common tool. The results of these two ecologists can be compared using the same metrics and, therefore, can be communicated much more efficiently. This should be a great advance in the task of unifying domains within ecology (Broszkiewicz, 2013).

Another advantage of having the PATh as a common tool to understand theory structure is that it reveals new niches for research collaboration. For example, if a model is frequently referred by different communities, these different communities should be sharing an interest in the same phenomenon. Because the questions related to the understanding of this phenomenon would be an interface between two different domains, it would be more efficiently filled by a study group with members of both communities (Lesser et al., 2009). The interpretation and use each community gives to the common model could reveal invaluable insights for the other community. Another scenario that reveals niches for collaboration is the identification of divergences between communities studying the same class of phenomenon. As argued, these divergences usually indicate a gap of knowledge. Because filling these gaps usually clarify the reason for the divergences, collaborations intended to fill the gaps of knowledge should also be of interest to members of both communities.

Concluding remarks

Some philosophers of science usually frown upon the pragmatic view argument because it, allegedly, could lead to a dangerous path to ignoring the role of explicit theories. On the other hand, some advocates of the pragmatic view, state that the propositions unifying the models of a theory cannot be identified because the set of models that compose the theory of a domain is an ever-changing set. Moreover, they argue that attempts to formalize the theory of a domain could pass on the wrong impression that theories are static entities, what could preclude the proper development of knowledge in a domain (Giere, 2010). The use of PATh shows that assuming the pragmatic view does not necessarily implies ignoring the role of explicit theories, and yet the assumptions behind the analysis frequently remind us that a single application is a mere photograph of an ever-changing structure.

It is not clear yet whether ecology can be considered a conceptually mature science. However, there is already a community devoted to answer this question (Hagen, 1989; El-Hani, 2006; Pickett et al., 2010; Scheiner and Willig, 2008, 2011; Marquet et al., 2014). One way to answer this question is to identify how scientists are building knowledge and what are the connections among the knowledge built. This should reveal the structure of the theory used in ecology, the conceptual gaps in this structure, and what is the role of the communities of researchers in this structuring. We think the PATh can contribute to this task because it aims exactly at the discovery of theoretical structures and conceptual gaps. By using PATh, members of the community will be able to communicate clearly how the research that is being conducted by ecologists are affected and affect the theory of ecology.

The proposal that theory in ecology can be organized into a hierarchical conceptual framework by Scheiner and Willig (2008) inspired us to reflect on the implications of developing an analysis to evaluate this thesis. We hope our proposed approach inspires others to engage in the discussion about theory structure in ecology. We think this kind of discussion will foster the building of a comprehensive agreement of what is ecological science.

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