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WHEN ECOLOGY AND PHILOSOPHY MEET:

CONSTRUCTING EXPLANATION AND ASSESSING UNDERSTANDING IN SCIENTIFIC PRACTICE

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Dissertation presented to the Program in History, Philosophy and Science Teaching at Federal University of Bahia and State University of Feira de Santana, to obtain the degree in Ph.D. in History, Philosophy and Science Teaching.

Supervisor: Charbel Niño El-Hani (UFBa)

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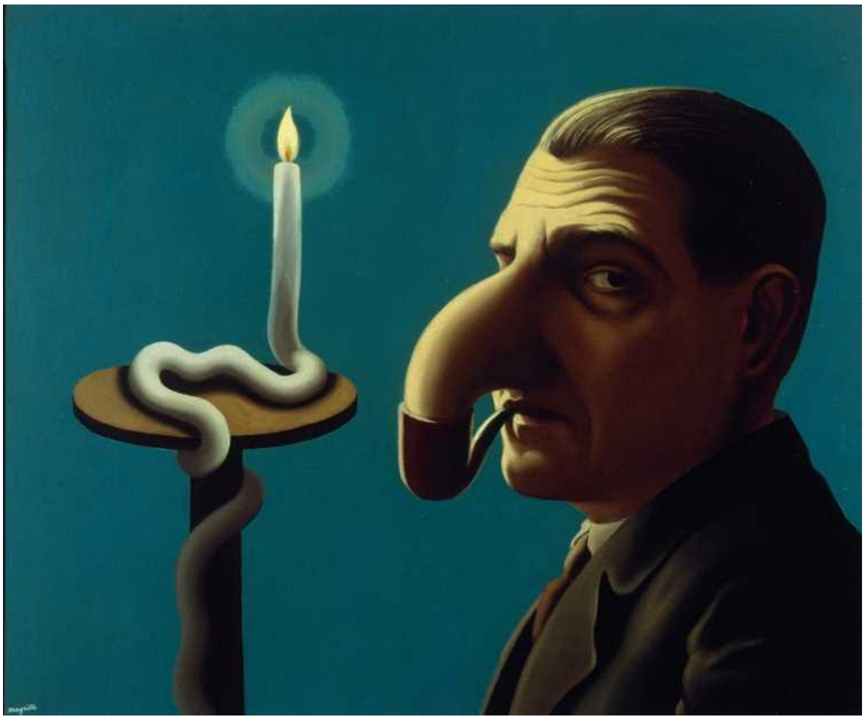
To women doing philosophy.



René Magritte
La lampe philosophique (1936)

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RESUMO

QUANDO A ECOLOGIA E A FILOSOFIA SE ENCONTRAM:

CONSTRUINDO EXPLICAÇÕES E AVALIANDO COMPREENSÕES NA PRÁTICA CIENTÍFICA

A filosofia da ciência em prática (*Philosophy of Science in Practice,* PoSiP) tem a prática científica como objeto de estudo. Porém, ela não possui uma metodologia geral ou específica que vise atingir seus objetivos. Em vez de se ater a um único protocolo, PoSiP tem a vantagem de utilizar diversos conjuntos de aplicações oriundas de diferentes áreas. Esta tese tem como ponto de partida uma pesquisa colaborativa e interdisciplinar entre dois doutorandos provenientes de campos distintos: ecologia e filosofia. Essa colaboração mostra como um cientista pode se beneficiar da filosofia da ciência (no estudo de caso dessa tese, da abordagem filosófica da explicação mecanística) para construir um modelo de seu *explanadum* via processo heurístico (heurística enquanto instrumento e abordagem metodológica). Mas também permite que a filosofia da ciência se aproxime da prática científica para investigar como as explicações são construídas e como a compreensão científica é atingida (nesta tese, em diálogo com a teoria contextual da compreensão científica). Como resultado desse trabalho, é defendido que: (i) a explicação mecanística é limitada mas pode trabalhar como instrumento epistêmico mediador entre teorias, dados, cientista e modelo; (ii) a construção de explicações e a compreensão científica dependem fortemente de um processo intuitivo; (iii) a compreensão científica é um momento, é transiente, um acontecimento temporário e seu processo pode ocorrer em níveis gradativos, (iv) a filosofia da ciência, por meio de um processo heurístico, pode aumentar as virtudes epistêmicas do cientista através do aumento de suas habilidades acadêmicas, via autorreflexão. Essa pesquisa mostra que trabalhos colaborativos interdisciplinares podem atuar, através de heurísticas, como uma caixa de ferramentas para a PoSiP atingir seu objetivo de entender como a ciência é feita. Apesar de seu sucesso, uma análise dessa prática colaborativa leva a alguns questionamentos fundamentais. Primeiro, a filosofia da ciência em prática é uma filosofia de uma prática científica pretérita, na medida em que a maioria dos exemplos utilizados pela PoSiP convencional é oriunda de produtos finais da ciência. Segundo, seria filosofia da [ciência em prática] ou filosofia da ciência [em prática]? Como praticar a filosofia da prática científica e como praticar interdisciplinaridade na filosofia da ciência em prática simultaneamente à atividade científica? Esta pesquisa expõe o papel epistêmico das heurísticas e da interdisciplinaridade como instrumentos metodológicos para a filosofia da ciência em prática. É defendido que outras formas de construção da ciência seriam através de diferentes dinâmicas, como redes colaborativas e pesquisas interdisciplinares, contribuindo para a visão de *trading zones* de Peter Galison, onde disciplinas especializadas criam pontes para trocas de conhecimento e informação.

Palavras-chave: Explicação mecanística. Compreensão científica. Heurísticas. Interdisciplinaridade. Filosofia da ciência em prática.

ABSTRACT

WHEN ECOLOGY AND PHILOSOPHY MEET:

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Philosophy of Science in Practice (PoSiP) has the "practice of science" as its object of research. Notwithstanding, it does not possess yet any general or specific methodology in order to achieve its goal. Instead of sticking to one protocol, PoSiP takes advantage of a set of approaches from different fields. This thesis takes as starting point a collaborative and interdisciplinary research between two Ph.D. students from distinct areas: ecology and philosophy. This collaboration showed how a scientist could benefit from philosophy of science (in this case study the philosophical approach of. mechanistic explanation) to construct a model of his *explanandum*, by means of heuristics approach (heuristics as an instrument but also a methodological approach) and, also allowed philosophy of science take a closer look into the scientific practice to investigate how explanations are constructed and how scientific understanding is achieved (in this thesis, with a dialogue with the contextual theory of scientific understanding). As a result, it is asserted that (i) mechanistic explanation possess limitations but may work as epistemic instruments that mediates between theories, data, scientists and models; (ii) explanation construction and scientific understanding deeply relies on intuition; (iii) scientific understanding is an instant, a moment, a temporary achievement, and its process may happens in degrees; (iv) philosophy of science, by means of heuristics process, may enhances scientists' epistemic virtues, improving his academic skills, by means of self-evaluation. This research shows that interdisciplinarity and collaborative work can act, through heuristics, as a toolbox for PoSiP to achieve its goal of understanding how science is made. Despite its success, an analysis of this collaborative practice leads to some fundamental issues. First, philosophy of science in practice is a philosophy of past practice, in that the majority of examples used by mainstream PoSiP come from the final products of science. Second, is it philosophy of [science in practice] or philosophy of science [in practice]? How to practice philosophy of scientific practice and, how to practice interdisciplinarity in the philosophy of scientific practices simultaneously to its scientific activity? This research exposes the epistemic role heuristics and interdisciplinarity possess as methodological toolboxes for philosophy of science in practice. It is defended that other ways of constructing sciences would be through different dynamics such as collaborative networks and interdisciplinarity research contributing to the vision of Trading Zones from Peter Galison, in which bridges between specialized disciplines are created in order to exchange knowledge and information.

Keywords: mechanistic explanation. Scientific understanding. Heuristics appraisal. Interdisciplinarity. Philosophy of science in practice.

OVERZICHT

WANNEER ECOLOGIE EN FILOSOFIE ONTMOETEN:

SAMENSTELLING EN TOETSING VAN BEGRIP IN WETENSCHAPPELIJKE PRAKTIJK

Filosofie van wetenschap in de praktijk (*Philosophy of science in practice*, PoSiP) heeft de praktijk van de wetenschap als object van onderzoek. Desalniettemin bezit het geen algemene of specifieke methodologie om zijn doel te bereiken. In plaats van vast te houden aan één protocol, maakt PoSiP gebruik van een reeks benaderingen uit verschillende velden. Dit proefschrift neemt als uitgangspunt een gezamenlijk en interdisciplinair onderzoek tussen twee Ph.D. studenten uit verschillende gebieden: ecologie en filosofie. Deze samenwerking liet zien hoe een wetenschapper kan profiteren van de wetenschapsfilosofie (*viz.* mechanistische verklaring) om een *explanandum* model van zijn uitleg te construeren, door middel van een heuristische benadering en (heuristieken als een instrument, maar ook als een methodologische benadering), ook toegestaan, de wetenschapsfilosofie om de wetenschappelijke praktijk nader te bekijken om te onthullen hoe uitleg wordt geconstrueerd en hoe wetenschappelijk begrip wordt bereikt (in vergelijking met de contextuele theorie van wetenschappelijk begrip). Dientengevolge wordt beweerd dat (i) de mechanistische verklaring heeft beperkingen, maar kan werken als epistemische instrumenten die bemiddelen tussen theorieën, data, wetenschappers en modellen; (ii) uitleg constructie en wetenschappelijk begrip vertrowt diep op intuïtie; (iii) wetenschappelijk inzicht is een moment, een tijdelijke prestatie en het proces kan in graden plaatsvinden; (iv) wetenschapsfilosofie, door middel van heuristisch proces, kan de epistemische deugden van wetenschappers verbeteren, zijn academische vaardigheden verbeteren, door middel van zelfevaluatie. In dit onderzoek laat ik zien dat interdisciplinariteit en collaboratief werk via heuristiek kan werken als een gereedschapskist voor PoSiP om zijn doel te bereiken om te begrijpen hoe wetenschap wordt gemaakt. Ondanks het succes leidt een meta-analyse van deze praktijk tot enkele fundamentele problemen. Ten eerste is de wetenschapsfilosofie in de praktijk een filosofie van de praktijk uit het verleden, bijvoorbeeld de meerderheid van de voorbeelden die worden gebruikt door de reguliere PoSiP komt van de eindproducten van de wetenschap. Ten tweede, is het filosofie van [wetenschap in de praktijk] of wetenschapsfilosofie [in de praktijk]? Hoe filosofie van de wetenschappelijke praktijk te beoefenen en hoe interdisciplinariteit in de filosofie van wetenschappelijke praktijken tegelijk met zijn wetenschappelijke activiteit te oefenen? Dit onderzoek legt de epistemische rol van heuristiek en interdisciplinariteit bloot als methodologische toolboxes voor wetenschapsfilosofie in de praktijk.. Er wordt verdedigd dat andere manieren om wetenschap te construeren door verschillende dynamieken kunnen zijn, zoals samenwerkingsnetwerken en interdisciplinariteitsonderzoek die bijdragen aan de visie van handelszones van Peter Galison, waarin bruggen tussen gespecialiseerde disciplines worden gecreëerd om kennis en informatie uit te wisselen.

Trefwoorden: mechanistische verklaring. Wetenschappelijk begrip. Heuristische benadering. Interdisciplinariteit. Filosofie van wetenschap in de praktijk.

LIST OF BOX, FIGURES AND TABLES

CONTENT

PREFACE

Before we dive into the traditional reading of this academic thesis, let me first tell you the story of how this project came to life and progressed.

This thesis started in 2014 with the idea of exploring the application of mechanistic explanation as a source of contributions to scientific practice, but the concept of such investigation dates back to a few years ago, during 2009-2014, with the project "Integrating Levels of Organization into Predictive Ecological Models: contributions from epistemology, modeling and empirical research" (INOMEP), funded by the Brazilian Program of Support of Nuclei of Excellence (PRONEX). The INOMEP/PRONEX project was already working with issues related to the prescriptive and descriptive nature of philosophy of science. One target of such appraisal was whether philosophy of science, in order to possess an identity of its own, needed to be prescriptive, and whether such prescription could be derived from scientist's descriptions of their own constructs. In this sense, prescriptions could be mirrored in heuristics.[1] By that time, we considered the new mechanistic philosophy of science as a possible field for developing a study on this kind of prescription, given its elucidation of how phenomena are often described and explained in biology and several other areas. The conjecture for INOMEP/PRONEX back then was to derive heuristics for ecological research according to the *modus operandi* of this new mechanistic literature that could have a prescriptive power. This was the root of this thesis project.

By the time this project started, mechanistic explanation was being applied mainly to create models in biochemistry, neuroscience, physics and sociological fields. Despite a few prominent discussions in the ecology of the early 1980's (*viz*. SCHOENER 1986), in more contemporary ecological science there are no strong discussions on how this type of explanation could be used. So, the question that emerged was: what if we could derive lessons from the (relatively) recent literature on mechanistic explanations in biology to create models of ecological phenomena? Well, it is no novelty that biology and ecology, in a sort of love and hate situation, have been using mechanisms to explain phenomena for centuries. The difference, at that point, was twofold. First, after Salmon's 1984 book *Scientific explanation and the causal structure of the world* and Bechtel & Richardson's 1993 *Discovering*

[1] The word heuristics in this thesis will possess three distinct meanings. 'Heuristics appraisal' will concern a methodological approach, 'heuristics set' will refer as toolbox (heuristics as tools will have two functions: instruments and displays), and 'heuristics process' will concern 'heuristics appraisal' and 'heuristics set altogether' (see section *'What is this thing called heuristics?'*).

complexity, mechanistic explanation had no ontological commitments with the philosophical and scientific tradition of mechanism any longer, being addressed by the new mechanistic philosophy of science. And second, mechanistic-model building, both in biology and ecology, until so far did not possess a theoretical framework that was strictly concerned with (the how-to of) mechanism-building.

So, my thesis had a goal and also a justification. But which ecological phenomena should be targeted? As a philosophy of science in practice research it was obviously needed to bind this project to a scientific practice in ecology. The solution came with the previous INOMEP/PRONEX, later improved to the INCT IN-TREE program. This thesis is embedded, thus, within the National Institute of Science and Technology in Interdisciplinary and Transdisciplinary Studies in Ecology and Evolution (INCT IN-TREE). The INCT IN-TREE is a research network coordinated by Charbel Niño El-Hani, funded by the Brazilian National Research Council of Scientific and Technological Research (CNPq) and the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES), and aims to develop projects in ecology and evolution in an interdisciplinary and transdisciplinary approach, involving mathematical, computational, and statistical modeling; epistemological and ethical studies; models for interaction with society; strategic communication; and technological development. This program includes 300 researchers and collaborators pertaining to 49 labs in 11 Brazilian universities and 35 universities and institutes all over the world. Facing the amount of ecological projects within INCT IN-TREE, how to choose one to work with? Well, two criteria needed to be contemplated for this selection. First, since mechanistic explanation was very much embedded in philosophical debates, the scientist going to collaborate with my thesis must be interested in incorporating aspects from philosophy of science in their research. Second, the timing of the joint research must fit into the schedule of both investigators in such a way that they might walk together without consequential delays. Fulfilling these expectations was the scientist (ecologist and modeler) Jeferson Gabriel da Encarnação Coutinho, a Ph.D. candidate in Ecology (supervised by prof. Dra. Blandina Felipe Viana) from the Bees Biology and Ecology Laboratory, also at Federal University of Bahia (UFBA), engaged in research concerning pollinators' dynamics in agricultural systems.

As you may perceive already, this research concerns a collaboration between two Ph.D. students, from distinct Ph.D. programs, with different thesis projects with distinct purposes. My main goal at that time was to investigate the contributions of philosophy of science to the scientific practice of model building. One of Coutinho's goals was to create a mechanistic model of pollinator's dynamics in agricultural systems that could allow him to derive management policies. Thus, to construct a model was the goal in common.

At this point my thesis had a "what", a "why", I have chosen a "which" but what about the "how"? Since this was a collaborative research project, we established that this investigation would happen through monthly meetings for a year. Thus during 2014-15, we gathered together to discuss philosophical and ecological literature in order to create heuristics that could guide him in the construction of a mechanistic model. Two things are very important to have in mind. One, that we have constructed the heuristics together but the ecologist was the only one to apply the heuristics in scientific practice. Second, that Coutinho applied the heuristics while their idea was still being conceived, so their construction and application happened concomitantly. It took us around a year to complete the heuristics set. By the end of 2015, we already had the impression that the mechanistic explanation would not succeed in explaining the phenomenon of interest, because of the intrinsic features of complex ecological systems.

Nevertheless, Coutinho continued to apply the heuristics and, by the year 2016, he realized that the mechanistic explanation was actually working to explain his ecological phenomenon. Therefore, a mechanistic model was successfully created and the philosophical literature, in his words, not only helped him develop his explanation but also helped him achieve a better understanding, by means of improving his technical skills. By the next year of this enterprise, 2017, the scientist at some point of his investigations realized that the mechanistic model was no longer necessary. He discarded the model and created a theoretical framework that he refers to as "unificationist". At the end of our collaboration this was his product.

What I want to reveal by telling this story is that my thesis, as a philosophy of science in practice investigation, started with a simple question. I wanted to know if mechanistic explanation, by means of heuristic processes, could help a scientist to create a model during his scientific practice. It was a "yes or no" answer conditioned to model building. I was considering only the scientist's creation therefore, perceiving science as a final product. Notwithstanding, I realized throughout this research that this product changed along the scientist's inquiry. These modifications made me wonder what happened during his analyses that led to these replacements. What happened in his scientific process? To answer these questions I needed to look at the scientific practice as a process instead of the scientific practice as a final product. In this sense, as the heuristics set served as an instrument for model building, I needed to disclosure its application. What I had not realized until then was that the reconstruction of scientific practice would be a puzzle with many missing pieces, sometimes because of methodological aspects inherent in collaborative/interdisciplinary research and sometimes because of the scientific process itself.

The real challenge of my thesis was not so clear at the beginning of this enterprise. It became clean and clear only in 2018 when I presented a draft of this thesis to the *Philosophy of Science and Technology* (FWT) group, at *Vrije Universiteit Amsterdam,* and at the *Workshop in Scientific Explanation and Scientific Understanding* at Ghent. Both events happened during my internship process in the Netherlands, at the *Universiteit van Amsterdam,* supervised by Dr. Federica Russo and funded by the Interuniversity Doctorate Exchange Program (PDSE/CAPES). After these conferences I realized that the main challenge of this research was how to practice philosophy of science in practice and how to deal with a philosophy of science that is interdisciplinary in its own practice. Facing such a thrilling enterprise, I might say by now that this thesis is an attempt to make sense and reconstruct the path of this maze called the philosophical and scientific practice of knowledge construction.

INTRODUCTION

Traditional philosophy of science (PoS) has aimed at an account of scientific knowledge in terms of a two-way relationship between world and knowledge (BOON 2017). The long tradition of philosophical literature about the nature of scientific explanation helps to reveal crucial features of explanation across the sciences (CRAVER 2007). Despite of it, much work in the philosophy of science continues almost isolated from scientific practice *per se* (ANKENY *et al.* 2011).

Philosophy of Science in Practice (PoSiP), besides other things, aims at an epistemology of scientific practices that addresses questions such as: how is the construction of knowledge for epistemic uses possible? It aims at an understanding of science that avoids the belief that the objectivity of knowledge can be warranted by an account of knowledge-justification that eliminates the role of scientists, but that also avoids a mere psychological and sociological interpretation of scientists' subjectivity (BOON 2017).

The Society for Philosophy of Science in Practice (SPSP) defines the term 'practice' as organized or regulated activities that aim to achieve certain goals. Thus, any investigation of practices should elucidate what kind of activities are associated with them and required for the generation of knowledge in a given domain. In this sense, PoSiP has the practice of science as its object of research. Notwithstanding, it does not possess any general protocol or any specific methodology to apply in order to achieve its goal. The instruments used to assess this scientific practice come from history, psychology, technology, sociology and so on, for instance, historical philosophy of science, sociology of scientific knowledge (SSK), science-technology-and-society (STS) studies (BOON 2017). The lack of a general methodological approach does not characterize PoSiP as more or less valid. The abovementioned instruments, with their interdisciplinary nature, constitute a toolbox to achieve the goal of understanding how science is made. Thus, the absence of an exclusive methodology transforms itself into a multitude of opportunities. Instead of sticking to one protocol, PoSiP takes advantage of a set or family of approaches from different fields. Now, the challenge is to map how these methodological processes might happen in such a cornucopia of possibilities.

Despite this amount and diversity of strategies, what is exactly at stake in philosophy of science in practice and how is it addressed? Is it philosophy of [science in practice] or philosophy of science [in practice]? Is the philosophy of science studying the scientific practice? Or is philosophy of science only being at practice when dealing with interdisciplinarity? How to practice philosophy of scientific practices; and how to practice interdisciplinarity in the philosophy of scientific practices in a way that is simultaneous to the scientific activity itself? Despite being referred to as 'real practice' or 'practice in the real world', PoSiP is often a philosophy of science of past practice. The majority of the examples used in the most recurrent debates come from the final products of science (*e.g.*, models, principles, etc., even when regarding explanation construction and scientific understanding). Therefore, the scientific practices responsible for the elaboration of these final products are, in the vast majority, narratives reconstructed usually from historical cases. In contrast, this thesis represents a different approach to PoSiP because it intends to show, through a case study in ecology, how philosophy of science in practice can walk hand to hand with ongoing scientific practice[2].

In order to tackle such a quest, this thesis reflects an interdisciplinary work in the philosophy of science in practice. It will be exhibited, through a case study in ecology, how a scientist can benefit from PoS (in a case study focused on mechanistic explanation) to construct a model of his *explanadum*. This was only possible because of the effort of a collaborative research between two Ph.D. students from distinct areas of knowledge: ecology and philosophy. This collaboration also allowed a closer look into the scientific practice in order to disclose how explanations in science are constructed and how scientific understanding is achieved, enlightening thus how a philosophy of science in practice can benefit from a partnership with science.

Lights, camera, action! The starting point

It is well known that explanations in biology often use mechanisms to provide understanding of living phenomena. Ecologists, for instance, use mechanisms not only to derive descriptive explanations of ecological systems but also to derive predictive models of those same systems. Notwithstanding, these mechanisms for long have been constructed with no solid framework concerning strategies of modeling and mechanisms construction[3]. So, if mechanisms are used to provide understanding, how can understanding exist when there is no cogent framework to enable it? Furthermore, acknowledging that ecology shares principles and methods with many other disciplines, how is the reliability of these explanatory predictive

[2] I appreciate Dr. Hans Radder's suggestions for this topic, made at the FWT meetings at VU.

[3] Is important to notice that mechanisms and models in biology and ecology are constructed mainly on the theoretical basis of a particular field, but not with regard to a theoretical framework dedicated specifically to elucidate the construction of such representations.

models achieved when the framework, needed to parameterizes those data at the construction of such mechanisms and models, is absent? And, how does the scientist understand the explanation and model he or she is constructing?

For over a few decades studies in the philosophy of science, especially those dealing with scientific explanations, have dedicated attention to understand how mechanisms and explanations are related in science. These studies were concerned with ontological, conceptual, causal, methodological and practical aspects of mechanisms and models, framing what became known as the new mechanistic philosophy of science. They engendered an attempt to construct a theoretical framework for mechanistic explanation that yielded a robust background for the construction of theoretical models involving mechanisms. Even though this theoretical framework is still under construction (being revisited with incredible quickness) it has been successfully applied to several areas of research. Unfortunately, the attempts to apply such knowledge to ecology are still shy[4].

Is it possible for these two areas, philosophy and ecology, to establish a dialogue to attempt to fill the gaps in the explanation and understanding of ecological systems? This was the leitmotif: can mechanistic explanation, by means of heuristics process, be used to explain ecological phenomena? Can heuristics help create explicative models in ecology, while in the making? Assuming that it would, how could this happen?

To answer these fundamental questions it was essential to integrate theoretical knowledge from both fields: ecology and philosophy of science. But how? Two Ph.D. students (one from HPS and another from Ecology) created heuristics to guide the development of an explanatory model of a specific ecological phenomenon. These heuristics were elaborated based on ecological theories and on the philosophy of mechanism. This communicative bridge was only possible due to mutual collaborative research between both Ph.D.'s, which also granted this thesis an interdisciplinary nature. As a result of this enterprise, it is possible to assert that mechanistic explanation was able to explain the ecological phenomenon at stake by means of providing an explicative model of the ecological system underlying it. Even though in a later moment this mechanistic model was discarded by the modeler in order to create a conceptual framework he deems as "unificationist", it is defended here that mechanistic explanation helped this framework development by means of a heuristic toolbox.

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[4] Such assumption comes from the survey made of the mechanistic literature (more details in the section on methodological features).

Thus, the first question that drove this thesis was answered, but what about the other ones: does this theoretical model satisfy the major features expected of an ecological explanation? If a predictive model was built, based on the heuristics, is it reliable and intelligible? In other words, how did mechanistic explanation (from which the heuristics have been derived, as instruments) help to explain and understand ecological phenomena? And how was the understanding achieved by the scientist? To answer these questions, I deemed necessary to take a deeper look at a major contemporary theory that deals with scientific understanding, the Contextual Theory of Scientific Understanding (CTSU), and zoom in the process that led to the model construction. This process occurred in two distinct moments: the heuristics construction and the heuristics application. When looking back at these moments it is possible to assert that these heuristics served as instruments toward the model elaboration and, according to the conceptual tools of the contextual theory of scientific understanding, they worked as displays to assess the scientific understanding of the modeler.

An important concern comes to life after the attempt at answering these questions. Ecology can indeed profit from philosophy of science by means of mechanistic explanation and model building via heuristic process. But how can philosophy of science benefit from ecology? To answer this question, it is needed to unravel the interdisciplinary and collaborative work as well as be attentive to the main pragmatic aspects of philosophy of science in practice. Such investigations will be addressed in the next chapters.

Methodological features

As a theoretical project, a philosophy of science in practice (PoSiP) research with an interdisciplinary and collaborative component, it is not an easy task to talk about methodological features. An attempt will be made in order to make these features more comprehensible from the beginning.

In philosophy of science in practice it is a common exercise to talk about multi- and interdisciplinarity but these discussions in ecological research are still apprehensive with no consensus on its terminology (TRESS, TRESS & FRY 2004). Previous section showed that for this research to achieve its goals it needed to be interdisciplinary and collaborative. The idea of interdisciplinarity adopted in this thesis comes from the distinction between multi-, inter- and transdisciplinarity proposed by Tress, Tress & Fry (2004) (Table A). Therefore, the majority of the discussions regarding interdisciplinarity in this thesis will gravitate around this definition, the partnership and the heuristics set derived from this collaboration.

A first aim of this interdisciplinarity was to answer if mechanistic explanation could be applied to ecology by means of heuristics process. For that it was necessary to bind knowledge from both fields: philosophy and ecology. This was reflected in a partnership between me, a Ph.D. student in History, Philosophy and Science Teaching, and Jeferson Gabriel da Encarnação Coutinho, a Ph.D. student in Ecology, both from the Federal University of Bahia (UFBa), Brazil. We gathered together to discuss the literature on philosophy of mechanisms and theories in ecology, in order to derive a set of heuristics that would guide model building. Thus, two things must be unambiguous: how these meetings happened and how was the heuristics set elaborated.

Table A: overview of proposed definitions of research concepts.

Disciplinarity	Takes place within the boundaries of currently recognized academic disciplines, while fully appreciating the artificial nature of these bounds and the fact that they are dynamic. The research activity is oriented towards one specific goal, looking for an answer to a specific question.
Multidisciplinarity	Involves different academic disciplines that relate to a shared goal, but with multiple disciplinary objectives. Participants exchange knowledge, but they do not aim to cross subject boundaries in order to create new integrative knowledge and theory. The research process progresses as parallel disciplinary efforts without integration.
Interdisciplinarity	Involves several unrelated academic disciplines in a way that forces them to cross subject boundaries. The concerned disciplines integrate disciplinary knowledge in order to create new knowledge and theory and achieve a common research goal. "Unrelated" means here that they have contrasting research paradigms.
Transdisciplinarity	Involves academic researchers from different unrelated disciplines as well as non-academic participants, such as land managers, users-groups and the general public, to create new knowledge and theory and research a common question. Transdisciplinarity combines interdisciplinarity with a participatory approach.

Source: Tress, Tress & Frys (2004:488).

These meetings, all of them recorded, occurred during a year with montly meetings. During that year we discussed the work in the new mechanistic philosophy of science[5] and the main theories in ecology relevant to Coutinho's work. It is important to highlight that one of the features of mechanistic explanation is its specificity in relation to mechanism-phenomena. Therefore, the process of heuristics conception and heuristics set definition was mostly based

[5] We surveyed the literature on the new mechanistic philosophy of science using the combinations of keywords "mechanistic AND explanation", "theories AND mechanistic AND explanation" "heuristics AND explanation", "causality AND science", "mechanism AND explanation", "mechanistic AND explanation AND biology" and "entities OR activities OR phenomenon" in the platforms Web of Science and Scopus. The articles from the ecological literature were those already being used in Coutinho's dissertation.

on the literature that already existed in the mechanistic literature, but adapted according to the features of the ecological phenomenon at stake.

After that year, more sporadic meetings were realized personally or virtually. Questions were also elaborated, whenever needed, in order to fulfill some information gap.

The dynamics of heuristics construction and application is illustrated in Figure Ia. During the discussions of the literature in the meetings, we elaborated together the general conception of each heuristics and the heuristics set. Concomitantly with this elaboration Coutinho was already applying the heuristics to model the ecological phenomenon. Whenever the heuristics were applied this worked as feedback for their improvement. Thus, the heuristics influenced the scientist's practice but the scientist's practice also influenced the heuristics. It is important to highlight that the construction of the heuristics general conception was a collaborative work between both Ph.D.'s. The elaboration of the theoretical framework for each heuristic was realized by me and the whole process of applying them to the ecological phenomenon was the sole and impressive effort made by Coutinho.

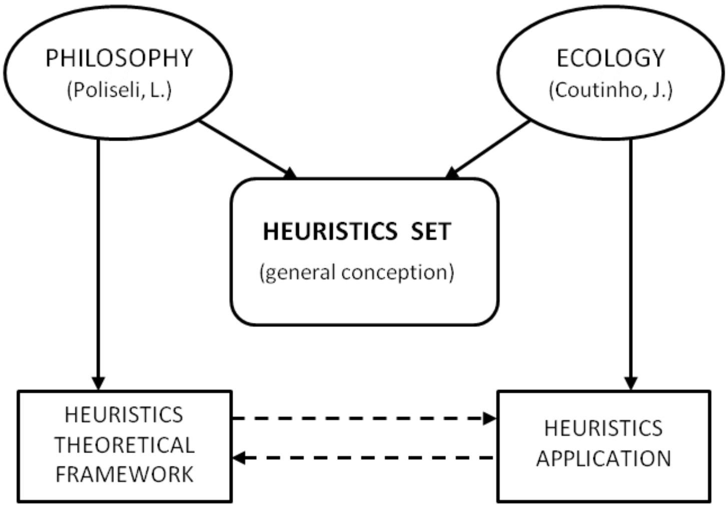
What is this thing called heuristics?

There exists a multitude of ways in which the term 'heuristics' is used throughout the different areas of knowledge. In cognitive psychology, for instance, heuristics is mostly described as efficient cognitive processes that help the subject make quick decisions and judgments (TODD & GIGERENZER 2000; GIGERENZER & GAISSMAIER 2011; BOBADILLA-SUAREZ & LOVE 2018). For statistics, heuristics is a simple algorithm that turns a vector data set into a similarity graph that is not guaranteed to produce an optimal solution (COFFIN & SALTZMAN 2000). In the legal field, heuristics are used as general principles that help proceed in an environment that is fundamentally uncertain or characterized by some degree of complexity (GIGERENZER & ENGEL 2006). Despite these different approaches, this thesis does not aim at somehow integrating them, but instead focuses on what these meanings ascribed to the term "heuristics" have in common: the potential of solving problems. In this investigation, heuristics will possess a three-way meaning: 'heuristics set', 'heuristics appraisal' and 'heuristics process' (Figure Ib).

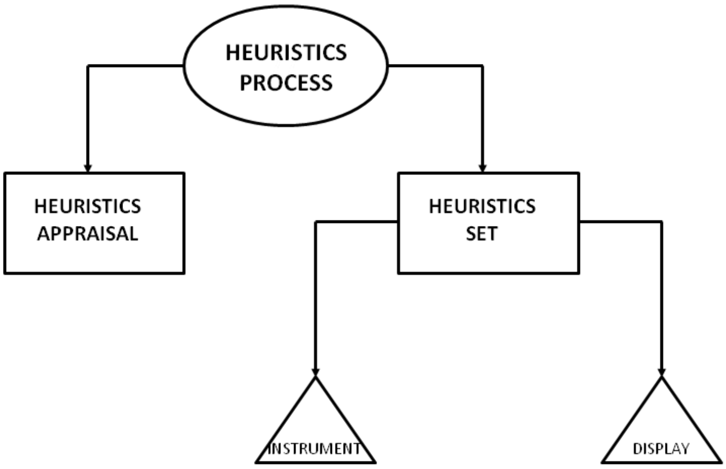
The first one, heuristics set, will be the heuristics toolbox to be used in this enquiry. Its utilization is twofold. In a first moment, it will serve as an instrument that will guide the scientist's actions for model building. And, in the second moment, the same heuristics set will serve as a display that will allow the philosopher to assess how the scientist created his explanation and achieved understanding of his *explanandum*.

Figure I: (a) Diagram illustrating the dynamics involving both Ph.D. students. **(b)** Diagram flow illustrating the relation between the different uses for the term 'heuristics' in this research.

(a)



(b)



Source: elaborated by the author.

The second one, heuristics as appraisal, targets the duality placed by Nickles (1989), namely whether science should occur according to an epistemic appraisal (EA) or a heuristic appraisal (HA). On the one hand, epistemic appraisal concerns the standard methods used by science, and is considered to possess a retrospective feature because it only allows the scientist to think about opportunities according to past results. On the other hand, heuristics appraisal is forward-looking and considers research as an ongoing process, open to the intrinsic features of a research process, articulating and aware of the evolving goals. Intermittently the word 'heuristics process' may appear, and for those moments it is referred to both: heuristics set being applied through heuristics approach.

The difference of EA in relation to HA relates to the possibility of facing questions such as: 'how do the sciences evaluate the promise, the fertility of a scientific result or proposal? How can scientists, in some cases, be so confident that problems (in the sense of difficulties yet unresolved) are solvable without substantial alteration of what is assumed as reliable knowledge? Why move in this direction rather than that? Why in this manner? (NICKLES 1989:176/7). HA is not only identified with original discovery or problem solving but mainly with the ability to deal with adversities and the prospect to trigger new fields of problems for investigation. And this is exactly why HA was chosen for this investigation, given the key role in it of the ability of the scientist to deal with the difficulties, which is often tacit in an ongoing scientific practice, *e.g.*, in the construction and application of the heuristics toolbox.

The third and last meaning, 'heuristics process' refers to both previous meanings altogether: the act of developing a heuristics set by means of a heuristics appraisal.

Thesis Overview

This thesis is divided into two parts. Each part possesses two chapters. This division was made according to the main goals in each part and will be presented below.

Following the *Introduction* there is the section *Understanding Explanation and Explaining Understanding*. This section aims to launch the reader into some major frameworks discussed throughout the thesis that are of paramount importance in PoSiP discussions, by exposing a brief overview on the historical debates related to scientific explanation and scientific understanding. Even though the mechanistic explanation literature could also be targeted in this section, I chose to expose its framework in *Part I* for an attempt to make clear the distinct investigations of this thesis. Therefore, Chapter One aims to give a brief overview about some major notions on which scientific explanation relies, and how they relate with the Contextual Theory of Scientific Understanding (CTSU). Considerations are made on how models and heuristics relate with explanation and scientific understanding.

Part I – Can Mechanistic Explanation Help Construct Models During Scientific Practice? The goal is to answer this very same question. To do so Chapter Two brings in the case study in ecology on which this thesis is based and exposes the final product of this investigation. Chapter Three will present the main discussions pertaining to the mechanistic literature and how mechanistic explanations are used throughout sciences. Considerations are made at the Preliminary Conclusions regarding the process of model building and explanation development in the case study.

Part II – How is Scientific Understanding Achieved During Scientific Practice? This part is intended to apply the Contextual Theory of Scientific Understanding to the case study in ecology. Chapter Four will zoom in the scientific practice of model construction and its relation to scientific understanding. Chapter Five explores how the process of achieving understanding happened in the case study and elaborates a model of understanding. The Preliminary conclusions discuss how the scientific understanding model relates with the scientific process of model construction and the contextual theory of scientific understanding.

Conclusions – Interdisciplinarity and heuristics as a toolbox for Philosophy of Science in Practice. This part defends tthat PoSiP can benefit from interidisciplinarity, via heuristics, as a toolbox to achieve its goal of understanding how science is made. And finish by bringing attention to some features of collaborative and interdisciplinary work that still need to be developed in further researches.

A clarification is needed in order to grasp the relation between the thesis parts and the collaboration in the case study. The mutual collaboration between me and Coutinho only took place in Part I of this research, and that is why is referred in the first person of the plural (=we). In Part II, however, the collaboration had ceased to happen. From this moment I step out from a position of collaborator and put myself exclusively in a position of philosopher of science. That is why from Part II onwards it is used the first person on singular (=I). This will also avoid further confusions that may happen concerning who is doing the investigation and what (sometimes who) is being investigated.

UNDERSTANDING EXPLANATION AND EXPLAINING UNDERSTANDING:
a historical debate in a nutshell

1 FROM SCIENTIFIC EXPLANATION TO SCIENTIFIC UNDERSTANDING

Explaining and understanding natural phenomena are the *raison d'être* of science (DE REGT & DIEKS 2005; BAUMBERGER, BEISBART & BRUM 2017). In early philosophy of science, mid-19th century, the notion of understanding has routinely been attributed to the notion of explanation, almost as if they were synonyms[6]. Even in the second half of the 20th century, examples can be found in philosophical works, such as Salmon's (1984:ix) *Scientific Explanation and the Causal Structure of the World*: "we secure scientific understanding by providing scientific explanations; thus our main concern will be with the nature of explanation". Thus, the importance of understanding was tacitly acknowledged but its nature and structure remained unanalyzed (DE REGT 2017:x).

Epistemological investigations, in a broad sense, used to pay attention to the nature and possibility of knowledge conceived as justified true belief, according to the classical definition stated by Socrates in Plato's dialogues *Theaetetus* and *Meno*. This was the starting point of contemporary epistemological discussions on the *value problem of knowledge*. Scientific understanding, in turn, had only become attractive to philosophers of science in recent decades with questions such as: what is understanding and what kinds of intellectual achievement does it constitute? (BAUMBERGER, BEISBART & BRUM 2017).

Explanations possess many virtues – for example, they may elucidate causal relations, describe underlying mechanisms, unify phenomena, shed light on the reducibility of a domain (TROUT 2005). Additionally, explanation does not only matter for its own sake but also because it may produce understanding. In spite of the massive debate concerning explanations and understanding in epistemology, the notion of understanding in science gravitates around two major accounts of scientific explanation: the causal-mechanical and the unificationist theories.

Section 1.1 of this chapter introduces the major theories of scientific explanation and exposes some examples of how they relate to biological explanations and, in particular, ecological explanations, besides introducing some instances from our case study of pollination services in agricultural systems. Section 1.2 exposes the contextual theory of scientific understanding (CTSU) and how it embraces both theories of scientific explanation,

[6] One of the reasons for such may be found in the etymology of the Greek word *episteme (*ἐπιστήμη), since in ancient philosophy *episteme* had the meaning of both knowledge and understanding (BAUMBERGER, BEISBART & BRUM 2017).

unificationist and causal mechanical, as conceptual tools for achieving scientific understanding.

1.1 Scientific explanations

1.1.1 The causal-mechanical theory

In the causal-mechanical conception, causality is the standard for intelligibility. Salmon's theory of causality reasons that "causal processes, causal interactions, and causal laws provide the mechanisms by which the world works; [thus] to understand why certain things happen, we need to see how they are produced by these mechanisms" (SALMON 1984:132). In such perspective, two elements are central: causal interactions and causal processes. Causal interactions generate and modify causal structure and causal processes are the way in which causal influences are transmitted (SALMON 1998). Therefore, "underlying causal mechanisms hold the key to the understanding of the world" (SALMON 1984:260). Salmon distinguished two forms of scientific understanding that would be merged, however, into what he regarded as a "final theory":

> In the course of this discussion, I shall examine two general forms of scientific understanding, both of which are available to us, and which are neither incompatible with each other nor contrary to the rigor and objectivity of the scientific enterprise. The first of these involves understanding our place in the world and knowing what kind of world it is. This kind of understanding is cosmological. The second involves understanding the basic mechanisms that operate in our world, that is, knowing how things work. This kind of understanding is mechanical. If, however, a final theory should be found, encompassing both practical physics and cosmology, then the two kinds of understanding would merge into one at the most fundamental level (SALMON 1998:81).

As discussed by De Regt & Dieks (2005), Salmon does not claim that causal-mechanistic explanation is a prior condition for scientific understanding because he acknowledges that this type of explanation is not applicable to all situations. Notwithstanding they argue that Salmon does not subscribe to a pluralistic position because he defends that causal analysis is the best one to provide understanding when compared to others. In other words, it is a privileged account toward scientific understanding.

Critics of the causal-mechanical conception assert that Salmon's model may not explain all domains of reality (cf. DE REGT & DIEKS' [2005] discussion of the Einsten-Podolsky-Rosen paradox). Furthermore, scientists sometimes choose not to use a model or theory even when it is applicable (*e.g.* Bohmian theory, *ibid*). Therefore, the causal-mechanical explanation will always face the possibility of being replaced in science, along the history of scientific thinking. And this places its intelligibility in an endangered position.

In biological sciences, however, the causal-mechanical account is widely used, especially in fields like neurobiology, molecular biology, biochemistry, among others (*e.g*. for explaining how neuron chemical synapses or protein synthesis work; see, for instance MACHAMER, DARDEN & CRAVER 2000, CRAVER 2007). Causal reasoning has also been widely employed in ecological studies, from the individual level, for instance to account for plant interactions with microbes and insects (PIETERSE & DICKE 2007), to spatial levels, for example, large-, meso-, small- and smallest levels as portrayed by the modeler in our case study (see Chapter 4, Sect. 4.3). For instance, the way the concept of functional diversity is used in ecology illustrates the importance of causal-mechanical reasoning, as it will also be clear in our case study, because functional explanations are used to causally connect aspects of biodiversity with processes and properties of an ecosystem (LOREAU 2010; DIAZ *et al.* 2007, REISS *et al.* 2009).

1.1.2 The unificationist theory

The unificationist conception, mainly defended by Friedman (1974) and Kitcher (1981, 1989), presents a very attractive image of what explanatory understanding should be. According to these authors, a theory that best provides a scientific understanding of the world is a theory that embraces and unifies other theories and/or a diversity of phenomena:

> Science increases our understanding of the world by reducing the total number of independent phenomena that we have to accept as ultimate or given. A world with fewer independent phenomena is, other things equal, more comprehensible than one with more (FRIEDMAN 1974:15).

> Understanding the phenomena is not simply a matter of reducing the 'fundamental incomprehensibilities' but of seeing connections, common patterns, in what initially appeared to be different situations. […] Science advances our understanding of nature by showing us how to derive descriptions of many phenomena, using the same patterns of derivation again and again, and, in demonstrating this, it teaches us how to reduce the number of types of facts we have to accept as ultimate (KITCHER 1989:432).

The major advantage of the unificationist theory is that its applicability is very general. After all, any theory is capable of providing understanding because it reduces the types of facts to derivation patterns: "no matter what its specific features are, if a theory turns out to be the maximally unifying systematization of a particular body of knowledge […] it provides genuine explanations and understanding" (DE REGT & DIEKS 2005:147).

As it is widely recognized, unification is important in science and has been playing important roles in the history of science (often cited cases in point are, *e.g.*, Maxwell's theory of electromagnetism and Darwin's evolutionary theory, see MORRISON 2000). But this does not mean that the quest for unification is always motivated by a desire of understanding, even though Kitcher (1989) assumes that understanding a theory is a requirement to produce scientific knowledge and to achieve understanding is deemed a cognitive ingredient: an internalization of the argument patterns. De Regt (2017:115) defends that in the unificationist notion understanding can only be achieved in an indirect way, in his words, "the understanding-providing feature of unification (in Kitcher's sense) is the fact that it allows us to see analogies between theories in the form of similar argument patterns, which extends the range of a particular skill".

De Regt & Dieks (2005) object that Kitcher's assertion is a *non sequitur* because reducing the number of arguments is not the only way to increase scientific understanding. For instance, they agree that seeking analogies between theories may help achieve understanding but they also recognize that understanding can be increased when scientists internalize one or two argument patterns instead of reaching a whole unification. For De Regt & Dieks (2005:149), this would be a preferable scenario since scientists would be better equipped to employ the separate argument patterns rather than the unified one.

As it has been already acknowledged by several authors, as, for instance, Leonelli (2009), biology is a very disunified science, and thus it is not a strange approach in contemporary biology to use an unificationist effort to connect different types of models and theories. One example of its application in biology is the emerging approach in taxonomy called integrative taxonomy. This approach aims to hold every sort of taxonomic evidence together (morphological, geographical, genetic, DNA barcoding data, and so on) in order to evaluate taxonomic categories and phylogenetic relations. Defenders of this procedure claim that it might solve disagreement among disciplines over the number and demarcation of species (SCHLICK-STEINER *et al.* 2010; for integrative taxonomy, see DAYRAT 2005; for different taxonomic traditions, see SIMPSON 1961; SOKAL & SNEATH 1963; HENNIG 1966; MAYR 1969; WILEY 1978; HULL 1988; NELSON 1989; CHRISTOFFERSEN 1995; DE PINNA 1999; AMORIM 2002).

In ecology it is not different. Ecological systems are influenced by multiple drivers at different spatial and time scales. Many of these drivers interact in a complex and non-linear way, which makes them very challenging to model. In such circumstances one alternative is to combine different principles in order to create a theory more adequate to explain complex systems. An example from our case study is the creation of predictive schemas by the modeler that combine two or more theoretical approaches of metacommunity theory: for instance species sorting and patch dynamics, or species sorting and mass effect (see Chapter 4, Sect.4.1.9). Another example from our case study is the model developed by the modeler at the end of his Ph.D. work, in which he brings together elements from distinct fields, namely the functional diversity of bees in an agroecosystem, and a conceptual framework unifying ecology, mechanistic explanation and complex systems sciences (Chapter 2).

1.2 Scientific understanding

1.2.1 The contextual theory

The contextual theory of scientific understanding (DE REGT& DIEKS 2005) elaborates on the idea of variations in standards of intelligibility in scientific practice, because it admits that scientific understanding should account for the contemporary and historical practice of science. Nonetheless, the intelligibility standards do not claim a status of exclusiveness and immutability because the authors recognize the importance of changing contexts. Therefore, to achieve understanding is a macro-level aim (considering science as a whole), even though a scientist's view at the precise moment when understanding is achieved may be contextually situated at a meso- (say, scientific communities) or micro-level (say, individual scientists) (DE REGT & DIEKS 2005:165, DE REGT 2017).

Considering that one of the universal epistemic aims of science is understanding, and scientific understanding of phenomena requires theories, which therefore must be intelligible, De Regt & Dieks (2005) assume intelligibility as a context-dependent feature concerning theoretical virtues as well as scientists' skills. Accordingly, intelligibility is needed for scientists to be able to use theories in order to generate explanations and predictions. From such a perspective these authors elaborate on the Criterion for the Intelligibility of a Theory (CIT) that incorporates pragmatic and contextual features of understanding:

> **CIT**: A scientific theory *T* is intelligible for scientists if they can recognize qualitatively characteristic consequences of *T* without performing exact calculations.

Therefore, in the contextual theory of understanding, a privileged status of particular standards of intelligibility (*e.g.* causality, visualizability, unifying power) as necessary conditions for understanding is not assumed. Instead, what is defended is that such intelligibility standards function as contingent tools to achieve scientific understanding because they help scientists intuitively see the consequences of a scientific theory, fulfilling then the requirements of CIT (DE REGT & DIEKES 2005).

1.2.2 De Regt's Account of Intelligibility

In *Understanding Scientific Understanding*, De Regt (2017) presents an improved version of the contextual theory of scientific understanding. He aims to construct a general theory of scientific understanding that should be pluralistic and independent of any specific model of explanation. This would allow the possibility that understanding be achieved via different explanatory strategies.

What is asserted by this theory is that to achieve scientific understanding it is first necessary to understand the theories used to explain phenomena, and, therefore, theories must contain arguments that are intelligible for the scientist to understand. In other words, "[o]nly intelligible theories allow scientists to construct models through which they can derive explanations of phenomena on the basis of the relevant theory" (DE REGT 2017:92). It is important to highlight that De Regt's intelligibility requirement relies on the following Criterion for Understanding Phenomena (CUP):

> **CUP:** A phenomenon *P* is understood scientifically if and only if there is an explanation of *P* that is based on an intelligible theory *T* and conforms to the basic epistemic values of empirical adequacy and internal consistency (*ibid*).

The basic idea of the theory continues to be that explanatory understanding requires intelligible theories. Regarding intelligibility, is important to notice that: (i) it is not an intrinsic property of theories but a context-dependent value ascribed to theories; (ii) it is defined as the value scientists attribute to the clusters of qualities of a theory that facilitate its use; and (iii) it is a measure of how fruitful a theory is for the construction of models by scientists in a particular context (DE REGT 2017:*passim*).

In an attempt to preclude the apparently purely subjective value judgment of (ii), De Regt elaborates a measure (iii) that allows the evaluation of the intelligibility of a theory according to its historical context (i), as follows:

> **CIT_1:** A scientific theory *T* (in one or more of its representations) is intelligible for scientists (in context *C*) if they can recognize qualitatively characteristic consequences of *T* without performing exact calculations (*ibid:*102).

The CIT_1 proposed by the author is appealing for pragmatic accounts of scientific practice and is in accordance with what is needed to understand a phenomena (UP) and to understand a theory (UT), as follows:

> **UP:** understanding a phenomenon = having an adequate explanation of the phenomenon (relating the phenomenon to accepted items of knowledge).
>
> **UT:** understanding a theory = being able to use the theory (pragmatic understanding) (*ibid*:91).

In our case study the CIT_1 demands are well reflected in several moments during the processes of heuristics application. One example is found in the heuristic "changes in operational components" (Sect.4.1.9), through which the modeler was capable of producing several predictive scenarios without the utilization of specific and precise instruments. These scenarios were developed after a meticulous evaluation of which approaches from the metacommunity theory should be employed to best fit the specificities of the phenomenon. This practice reflects some sort of understanding of the theories (UT) that the modeler was dealing with and are required for the understanding of the phenomenon of interest (UP).

The theory of intelligibility relies, then, not only on the qualities of the theory *per se*, but also on the scientists. The capacity of scientists to judge the intelligibility of a theory will depend, in turn, on their skills and background knowledge. In such a scenario, scientists need *conceptual tools* associated with their *skills* to use a specific theory in order to generate explanation and understanding of the phenomena (DE REGT & DIEKES 2005; DE REGT, LEONELLI & EIGNER 2009). According to the history and practice of science, scientists will choose the tools that are more apt to achieve their goals, and for attaining understanding. Therefore, there exists a variety of such tools, according to the period and disciplines. Examples of these conceptual tools are: visualizability, causal reasoning, continuity, mathematical abstraction, and others (DE REGT 2017:85).

The author also suggests that there might exist a link between visualization and understanding, and between visualizability and intelligibility. Visualization is regarded as a useful guide to achieving scientific understanding, while visualizability is a theoretical quality that may enhance intelligibility. Visualizable theories are often regarded as more intelligible than abstract ones, because many scientists prefer visual reasoning in the construction of explanations of phenomena, using pictorial representations or diagrams as tools. Several scientists in the history of physics have relied on visual power to enhance a theory. Examples include Richard Feynman's diagrams and Erwin Schrödinger`s defense that the only way to acquire understanding of nature is to build theories visualizable in space and time. However, visualization is not a necessary condition for understanding (*ibid*).

In our case study, visualizability played a major role in intelligibility, as it will be clear in the heuristics "mechanism schema" (Sect.4.1.2), "hierarchical structure" (Sect.4.1.3) and "changing in operational components" (Sect.4.1.9). The construction and visualization of pictorial diagrams by the modeler helped him in structuring his theoretical background and in organizing data related to the phenomenon (Chapters 2 and 4).

Causal reasoning functions as a tool not only because it allows us to explore the underlying structure of the world, but also because it improves the abilities concerning predictions of a specific system under particular conditions. De Regt (2017:115) also asserts that this view is closely connected to Woodward's (2003a, 2003b) manipulationist theory of causation, because it defends that scientific understanding can be achieved by being instrumentally successful in answering questions about the behavior of a system.

Other tools also related to causality aspects are productivity and continuity. The productive continuity is the capability of a system, a causal mechanism in this case, to be intelligible. Intelligibility for such a mechanism relies on the explicit connections between the stages in a mechanism, in other words, the continuity of the actions between the components. In other words, a mechanism is more intelligible when there are no gaps or black boxes interfering with the clear exposure of the relations among its components (MACHAMER, DARDEN & CRAVER 2000). In our case study of pollination services, the causal reasoning functioning as conceptual tool is represented in the heuristics "operational component distinction" (Sect.4.1.5) and "evidence frequency" (Sect.4.1.6).

As one may have already realized, the conceptual tools are not isolated in themselves; on the contrary, they might add to each other in order to grant the necessary intelligibility of the hypotheses or theories or propositions. It is in this sense that the unifying power functions as a tool. To sum up, conceptual tools allow skilled scientists to recognize the features and consequences of a scientific theory and thereby facilitate model building.

According to De Regt (2009, 2017), skills and judgment cannot be reduced to rule-following procedures because they change according to the historical, social or disciplinary context. Such skills will depend on which theory the scientist is dealing with, and on the pragmatic virtues of it. For instance, the construction of a model relies on a specific theoretical framework that demands from the modeler specific skills concerning the theoretical properties. Those skills may vary from expertise techniques (*e.g.* lab work, data collection), to grasping and intuitive judgment.

De Regt (2017) elaborates on Gigerenzer's (2007) psychological notion of intuitive judgment, according to which intuitive judgments are not obscure, but, on the contrary, are produced by heuristics usually developed in an evolutionary process of adaptation to the environment. Gigerenzer (*ibid*) acknowledges the reliability of intuition and its role in decision-making processes, and defines intuition as judgment that arises immediately in consciousness, without full awareness of underlying causes (for contrary views, see KAHNEMAN 2011):

> While Gigerenzer focuses on decision processes in everyday life and professional contexts, it seems plausible that similar mechanisms are at work in scientific practice. This would support my thesis that skill and intuitive judgment play a central role in the process of achieving scientific understanding. If a theory is intelligible to scientists because its theoretical qualities match their skills, they can reason "intuitively" with it. Like our everyday intuitive skills, scientists' skills are the outcome of a complex learning process in which their evolved cognitive capacities interact with the environment in which they find themselves (that is, the historical and disciplinary context of their science) (DE REGT 2017:110).

The notion of grasp plays a minor role in De Regt's intelligibility account. He asserts that the intelligibility of a theory implies the possibility of grasping how its predictions are generated. He acknowledges that grasp is a feeling for the consequences of the theory in concrete situations, being a rough, general idea, not an emotion or an immediate intuition. Grasping, then, suggests that it is possible to understand how a theory works without being able to use it for making calculations (*ibidem*). Even though De Regt highlights this difference, it appears that the notion of grasp is closely related to the notion of intuitive judgment, and perhaps this could be one of the reasons for grasp being a secondary element in his theory. The notion and role of grasp generate a highly controversial debate and will be readdressed in subsequent chapters.

The criteria for understanding and intelligibility presented by De Regt form the basis of an account of scientific understanding in which explanation, understanding and prediction are interrelated epistemic goals of science. Scientists use their expert skills to construct models of the object or system they want to understand scientifically. Model construction is partly a matter of making the right approximations and idealizations, which require skillful uses of the available conceptual tools. The ability to predict – the recognition of qualitative consequences of the theory, as expressed in CIT_1 – shows that scientists have such understanding, or in other words, that the theory is intelligible to them.

1.3 Final considerations

This chapter presented the main theories of scientific explanation and how they are embraced by the contextual theory of scientific understanding. The CTSU defends that the unificationist and causal-mechanical theories of explanation are used as instruments, the conceptual tools, helping scientist achieve understanding. Some examples of their employment in biology, ecology and our case study were preliminarily provided. What will be shown in Chapter 3 (Preliminary conclusion) from our case study is that the causal-mechanical theory provided the starting point for model building and explanation development. Notwithstanding, during the process of modeling and explaining it was possible to perceive a shift from mechanistic to unificationist reasoning. It will be explicitly exposed in Chapter 4 that both accounts of scientific explanation were successfully applied for the purpose of explaining our case study of pollination services in agricultural systems. Why did these subtle changes happen and how did the scientist perceive his data, phenomenon and explanation? To answer these questions, it is necessary to take the heuristics out of the black boxes, and expose how they were applied. If we grasp how the modeler elaborated his explanation step by step, we may be able to solve these issues. The better way to do so is to evaluate his scientific practice by means of the contextual theory of scientific understanding, since this is the only theory of understanding that considers the scientific practice as content- and context-dependent. An assessment of how the modeler understood the model and explanation he constructed will be developed in Chapters 4 and 5.

PART I

Can mechanistic explanation help scientists construct models during scientific practice?

INTRODUCTION

Unraveling what a scientific explanation consists of has been one of the most central topics in the philosophy of science throughout the twentieth century (BRAILLARD & MALATERRE, 2015). Although explanations in biology by means of mechanisms have long been debated, most recently in relation to different fields of science such as neurobiology, molecular biology, and sociology, there has appeared a new philosophical debate about mechanisms and explanations at the turn of the 21st century (MACHAMER, DARDEN & CRAVER 2000). Unlike the reductionist view of the classical causal-mechanical relation, this approach – the new mechanistic philosophy of science – embodies new perspectives on mechanistic explanations, which intend to take into account notions such as hierarchical levels and complex systems (BECHTEL & RICHARDSON [1993]2010).

Roughly, a mechanistic explanation requires providing an account of a mechanism to explain a particular phenomenon. Most scientists who adopt this view assume that behind every phenomenon in nature, there exists a mechanism that produces it and thus can help us unravel how the phenomenon comes to be. Thus, to describe such mechanism is to explain the phenomenon *per se* (CRAVER & BECHTEL, 2006:469). In other words, “much of the practice of the science can be understood in terms of the discovery and description of mechanisms” (MACHAMER, DARDEN & CRAVER 2000:2). In the light of it, the focus of *Part I* of this thesis lies in this sort of scientific explanation, the mechanistic one.

In spite of the literature on mechanisms been hunched mainly over historical cases, the idea of this thesis is to work with science in the making. We intend to investigate the contributions of the literature on the new mechanistic philosophy of science for the scientific activity of building explanatory models in ecology. What is being questioned here is not only the prospect of this sort of explanation be as successfully applied to ecology as it is to the other sciences quoted above, but also if heuristics developed from the philosophy of science can contribute to ecology in the making. Therefore, this chapter will reflect on the interaction between – two distinct but nevertheless connected – epistemological and ecological projects, in order to answer the following question: can the new mechanistic explanation, by means of heuristics, helps scientists construct models while doing science in practice?

There are a few records so far of the new mechanistic explanations applied to ecological studies (see PÂSLARU 2009, 2015), suggesting that the dialogue between the philosophy of science and ecological sciences can be fruitful, justifying the intentions of the current work.

Regarding the ecological project at stake, there exists an interest (concerning management) in developing a model for a specific phenomenon in ecology – the community organization of autochthonous bees and pollination service maintenance in agricultural systems, which constitutes our case study. And with respect to the epistemological project, there exists an interest in realizing if the mechanistic explanation is viable to explain ecological matters, and if heuristics developed from the philosophical literature can contribute to ecology in the making. Thus, on one side of the study, we need to consider ecological knowledge about the phenomenon itself, and on the other knowledge arising from the literature on mechanistic explanation in recent philosophy of science. These conceptual bases combined provided information that enabled the development of a heuristics set. These heuristics served as a guideline for model construction.

As already stated in the Introduction to the thesis, with the utilization of the heuristics set the mechanistic model was successfully constructed by the modeler. We already know that this model was discarded by the scientist in order to create a theoretical framework that he describes as "unificationist". The idea of Part I is to show what is our case study, what is this new mechanistic philosophy of science, how is the heuristic set composed, what is the mechanistic model created, and at last what is the theoretical framework that emerged from this process. In this sense, Part I is structured as follows. Chapter 2 presents our case study "the community organization of autochthonous bees and pollination service maintenance in agricultural systems" and its main features. Chapter 3 brings major ideas from recent philosophical studies on mechanistic explanation conjoint with more classical efforts to elucidate this kind of explanation. Preliminary conclusions will be drawn with the exposition of the heuristics set elaborated according to the information derived from Chapters 2 and 3, besides presenting the mechanistic model and theoretical framework created by the modeler. It is important to highlight, that the heuristics set will be only presented as a table in this part of the thesis. Its main theoretical content and how it was constructed will follow in Part II.

2 FUNCTIONAL COMPOSITION OF AUTOCHTHONOUS BEE COMMUNITIES IN AGRICULTURAL SYSTEMS

The new mechanistic philosophy of science has been very successful when used to account for how mechanistic explanation is carried out in several scientific areas, such as biochemistry (Na+ channel depolarization), molecular biology (DNA transcription), neuroscience (neuronal chemical synapses), and so forth. Notwithstanding, this kind of explanation has been less frequently applied to ecological systems, and there were also less philosophical works devoted to elucidate mechanistic explanation in ecology, as we perceived from the outcomes of a literature survey performed as exposed in the section "methodological features" above. One of the putative reasons, we believe, it is because ecological systems are influenced by multiple drivers at different spatial and time scales (NELSON *et al.* 2006). Many of these drivers interact in a complex and non-linear way, adding to the challenges of modeling ecological systems and processes, especially from a mechanistic perspective. But considering that the new mechanistic perspective deals with multilevel systems with inputs and outputs, and also with features like hierarchies and nonlinearities, arose the issue whether mechanistic explanation conceived according to this perspective could help ecology in the process of explaining and building models for dealing with these complex and non-linear drivers.

This chapter aims to expose major theories and principles in ecology that are most relevant for our case study (*the functional composition of autochthonous bee communities in agriculture systems*), according to the modeler himself. Section 2.1 will expose what is the phenomenon we are dealing with and some intrinsic features of it. Section 2.2 will address the most relevant ecological concepts, principles and theories connected to our case study.

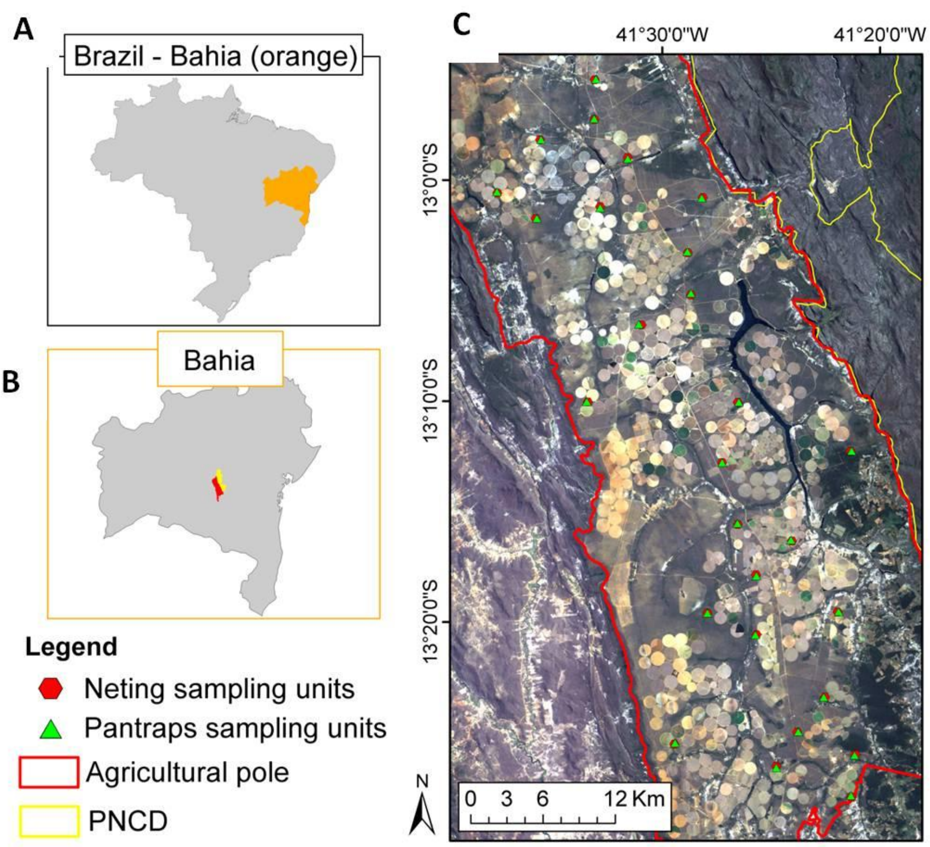
2.1 Why bees?[7]

The ecological phenomenon of this endeavor is entitled by the modeler as the *functional composition of autochthonous bee communities in agriculture systems* in the Mucugê-Ibicoara agricultural pole, Chapada Diamantina National Park (PNCD), Bahia, Brazil (Figure II). This complex sentence, in other words, means that what it is going to be investigated and modeled is how the community of native bee's organize themselves in relation to their functional role (such as pollination) in agricultural systems located inside this National Park.

[7] see Coutinho (2018: *manuscript*).

Why bees? Bees are the most important organisms concerning pollination services in most regions of the world (KLEIN *et al.* 2007). They are responsible for the pollination of approximately 70% of crops around the world and for the pollination of more than 80% of angiosperms. Agricultural systems show an intricate set of ecological and non-ecological characteristics that define their dynamics. For instance, decisions in landscape management that aim at suppressing native vegetation may affect negatively several groups of species, through habitat loss. These groups may be involved in different ecosystem services, *e.g.* water depuration, nutrient cycling in the soil, biological pest and pollination control. All these services are intimately connected with food supply for human societies and other biological communities (COUTINHO, *personal communication*).

Figure II: (A) Brazil represented in gray and Bahia state represented in orange; (B) within Bahia state, the studied area is shown in red and Chapada Diamantina National Park in yellow; (C) geographical delimitations of the studied area.



Source: modified from Coutinho (2018:*manuscript*).

The medium and long-term forecast is that intensive land use is not consistent with the management stability of agricultural systems in time and space. To keep stability, it will be necessary to restructure land use so as to be compatible with biodiversity conservation and ecosystem services. This is the reason why the connection between biodiversity and ecosystem services has been proposed via functional diversity of ecosystem services providers (ESPs). Such assumption is accepted because of the unequal contributions of distinct species for the magnitude or stability of ecological functions related to ecosystem services. (COUTINHO 2018:*manuscript*).

2.2 Ecological framework[8]

The ecological framework exposed in this section was selected by the scientist according to what he judges relevant for the phenomenon to be modeled. This framework was referred by him as the "main theoretical pillars" in which the phenomenon lies on, and consequently it was analyzed together with the mechanistic literature for the elaboration of the heuristics set. This framework includes: (i) theories in landscape ecology, (ii) properties of complex systems, (iii) natural history of the system's attributes (e.g. plants and bees), and (iv) metacommunity theories. In order to provide a better picture of our case study, we will describe each component of the theoretical framework in turn.

Landscape ecology is characterized by two distinct views: (a) a geographic approach, and (b) an ecological approach. The first one concerns the interactions between human beings and their environment, while the second one focuses on ecological processes and patterns. An integration between these approaches has been proposed by Metzger (2001), as we will expose below.

The geographical approach studies the influences of human beings over the landscape, considering in particular how we manage the territory. There are three main issues that characterize this view: (i) the concern about planning the territory occupation; (ii) the study of the landscape deeply modified by human beings – the 'cultural landscape'; and (iii) the analysis of such large areas. In this sense, landscape ecology is not focused on bio-ecological studies and may be defined as a holistic discipline. This perspective combines knowledge from several areas, such as sociology, ecology, biogeography, geology, and geography. Its main goal is the total understanding of the landscape (mostly cultural) and the territory planning (METZGER 2001).

In turn, the ecological perspective emphasizes the importance of the relation between ecological processes with their spatial context for biological conservation. In this view landscape is characterized as (i) a heterogeneous area composed of a cluster of interacting

[8] The information of this section was extracted from Coutinho (2018:manuscript) and *personal communication*.

ecosystems; (ii) a mosaic of distinct landforms, diverse vegetation, and land usage (see URBAN *et al.* 1987); and (iii) an area spatially heterogeneous. This approach favors the natural landscape, and the use of landscape ecology for biodiversity conservation and management of natural resources (METZGER 2001).

Metzger's effort is virtuous because it realizes that these two perspectives do not exclude each other. Instead, they can be quite complementary since both are spatially explicit, deal with heterogeneous spaces, and consider multiples scales in the analysis. The unified notion advanced by Metzger conceives the landscape as "a heterogeneous mosaic composed by interactive landscape units, where heterogeneity exists for at least one parameter, one specific observer and a particular scale" (METZGER 2001:1). Thus, the landscape continues to be a visual entity that is entirely dependent on the observer and the scale at which it is observed.

Considering the second "main pillar", *properties of complex systems*, it was necessary to make choices among the several definitions and debates about complex systems in the natural sciences (see BERTALANFY [1968] 2014), economy (see FERGUSON *et al.* 2003), epidemiology (see HALDANE & MAY 2011), education (see MORIN, 2014), and other fields. In this research we adopt the idea of *complex systems* as showing eight attributes (FILOTAS *et al.* 2014): (a) heterogeneity, (b) hierarchy, (c) self-organization, (d) openness, (e) adaptation, (f) memory, (g) non-linearity and (h) uncertainty (see SOLÉ & GOODWIN 2000; BOCCARA 2004; MITCHEL 2009). These properties are found in a variety of biological, social and physical systems, which are the objects of study of *complex systems science* (CSS) (MITCHEL 2009, FILOTAS *et al.* 2014:2). CSS enables to yield insights and comparisons between complex systems and is useful for understanding ecosystem structure and dynamics. This approach will be extremely important concerning our ecological phenomenon to be modeled because it can be used in systems of all scales, sizes, and functions (FERGUSON *et al.* 2003, FILOTAS *et al.* 2014:2).

Complex systems are systems with usually distinct components that interact over a variety of spatiotemporal scales (see LEVIN 1992; GREEN & SADEDIN 2005). Such interactions cannot be calculated simply by the summing of the dynamics of individual components because they produce a variety of reactions that guide the system dynamics. Thereby, *heterogeneity* is an important characteristic of the dynamics of complex systems and is also crucial to the management of their response and resilience (FILOTAS *et al.* 2014). This heterogeneity is evidenced by the nature of the components, their behavior, structural organization, spatial localization, and history.

The second attribute, *hierarchy,* asserts that the components of a complex system are organized hierarchically at different levels or scales. This multilevel structure assures a network where the phenomenon is realized through the interaction between the scales (see SIMON 1962; LI 2000). In the hierarchical model advanced by Filotas *et al.* (2014:6), the most different dimensions are considered, such as ecosystem services, forest products (and their users), local communities, government, and social and economic scope of industries.

Self-organization, the third attribute, concerns a series of actions between the components at one level that results in a product at another level. This may affect other components trough feedback (see PERRY 1995; LEVIN 2005). Self-organization occurs spontaneously and is frequently connected with the emergence of remarkable spatiotemporal patterns (FILOTAS *et al.* 2014).

The fourth attribute, *openness,* means that the dynamics of the system are influenced by outside factors. Due to cross-scale interactions and emergent phenomena, these dynamics are not easy to delimit (CUMMING & COLLER 2005; FILOTAS *et al.* 2014).

Adaptation, the fifth attribute, is the capacity of the system to adjust towards disturbances resulting from external inputs. Such attribute is intimately related to the concept of ecosystem resilience (GUNDERSON & HOLLING 2002, FILOTAS *et al.* 2014). Notwithstanding, the difference between these concepts is that adaptation allows the system to modify and reorganize its components and functions when confronted to disturbances (PARROT & LANGE 2013, FILOTAS *et al.* 2014), and ecological or ecosystem resilience refers to the capacity of the system of absorbing change and disturbance without changing its behavior regime (HOLLING 1973, GUNDERSON 2000). A behavior regime can be defined as a series of stable states that repeat themselves over time, with a certain periodicity but not precisely. When disturbed up to a certain limit (the resilience threshold), the behavior regime shifts to transient states for a time interval but eventually returns to the repeating series of states. There can happen, however, that disturbance surpasses the resilience threshold and then shifts in behavior regime take place, leading to a different kind of system in relation to the system that previously existed.

The sixth attribute, *the memory of a complex system*, concerns the information from past events that influences future dynamics of a system and, accordingly, its structure and composition through feedbacks and constraints (ANAND *et al.* 2010, PARROT & LANGE 2013). This memory may act, in complex systems, as an important agent of resilience (FILOTAS *et al.* 2014).

The seventh attribute, the *non-linearity* in a complex system, is related to disproportional output responses to input stimulus. Thus, the system dynamics may present large or small responses according to the type or amount of variance. Non-linearity and feedbacks are important features for the regulation, spatial synchrony and chaotic dynamics in all ecosystems (see CONSTANTINO *et al.* 1997; BLAUSIUS *et al.* 1999; FILOTAS *et al.* 2014).

The last attribute, *uncertainty*, deals with the unpredictability of the system dynamics and it may surface from several sources. One such source is the stochasticity of the internal processes in the dynamics of socioecological systems. Another source of uncertainty is non-linearity that may cause regime shifts. A third source is openness, as complex systems are vulnerable to changes in external systems to which they are associated. Historical and natural events such as tsunamis, wars, etc. may reinforce this attribute. The last source of uncertainty lies in the very adaptiveness of the system (FILOTAS *et al.* 2014).

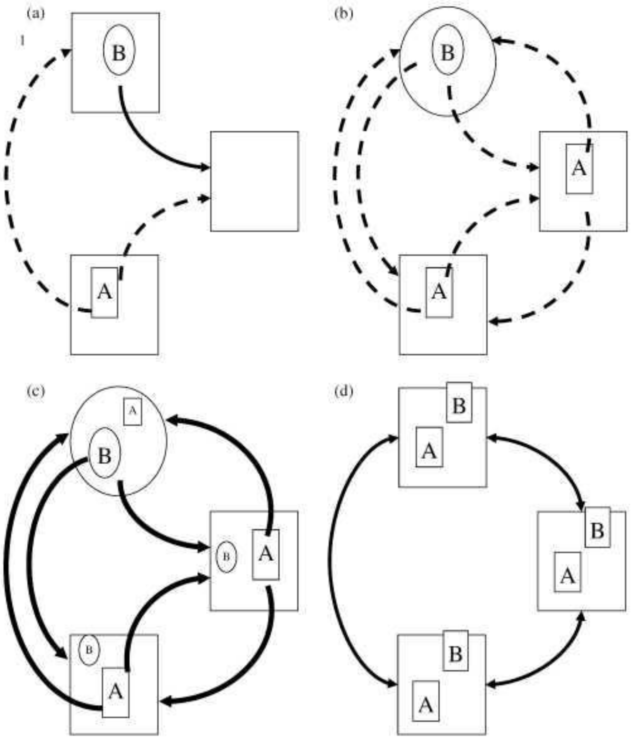
The *natural history of fauna and flora*, the fourth pillar in the framework, corresponds to the available biological information about the species involved in the process of pollination. This information exposes the distinctiveness of each group in terms of its evolutionary process, food, behavior, reproduction dynamics, as well as their interactions with each other and with the environment.

Finally, the *metacommunity theories* provide principles that explain ecological patterns at large scales. There are four main views about metacommunities: (a) the patch-dynamic view, (b) the species-sorting view, (c) the mass-effects view, and (d) the neutral view (Figure III). Metacommunity theories provide an important approach to think about linkages between different spatial scales in ecology (LEIBOLD *et al.* 2004:*passim*).

The patch dynamic perspective (Figure IIIa) emphasizes the existence of numerous community patches that are alike to each other. Each patch has the potential to contain populations. However, they may be occupied or unoccupied. These patches are engaged in stochastic and deterministic extinctions that can be influenced by interspecific interactions, and are restrained by dispersal. In other words, local species diversity is limited by dispersal and spatial dynamics are dominated by local extinction and colonization (LEIBOLD *et al.* 2004:604-605).

The species-sorting perspective (Figure IIIb) asserts that local patches are different in some features and the consequences of local species interactions depend on aspects of the abiotic environment. In other words, there are trade-offs among species and environment that allow them to specialize in a variety of patch. This reflects a strong difference in the local demography of species in the communities, revealing changes over environmental gradients. This approach presupposes a spatial niche separation above and beyond spatial dynamics, and a separation of time scales between local population dynamics and colonization-extinction dynamics. Thus, dispersal is significant because it allows compositional modifications to track changes in local environmental conditions (LEIBOLD *et al.* 2004:604-607).

Figure III: Four representations of metacommunity theories: (a) patch-dynamic perspective; (b) specie-sorting perspective; (c) mass-effect perspective; and (d) neutral.



Source: Leibold *et al.* (2004:606).

The mass-effect perspective (Figure IIIc) focuses on the effect that spatial dynamics has on local population densities through immigration and emigration. For instance, species may be rescued from local competitive exclusion in communities where they are bad competitors by immigrating from communities where they are strong competitors (LEIBOLD *et al.* 2004:604). Dispersal acts then as a source-sink relation amongst populations in distinct patches which may affect the relations between the local conditions and the community structure (HOLT 1993, MOUQUET & LOREAU 2002:200, LEIBOLD *et al.* 2004:607).

The neutral perspective (Figure IIId), in contrast with the other three approaches, may be described as a null hypothesis (BELL 2001, LEIBOLD *et al.* 2004:608). Its possible to consider that all species are similar in their competitive ability, movement, and fitness (HUBBELL 2001, LEIBOLD *et al.* 2004:604). In this model all species are currently present in all patches, but they will be gradually lost in patches and will be replaced by speciation (LEIBOLD *et al.* 2004:606). Therefore, metacommunity dynamics consist of random walks that alter relative frequencies of species in space through time (Leibold *et al* 2004:604/608).

Most agricultural systems presuppose a certain kind of landscape management. This management possesses a few features that influence any given phenomenon within this system. To deal with such dynamicity two characteristics are usually addressed in the ecological literature: distance between fragments and diversity of habitat types.

The *distance between floral fragments* may influence pollinators' movement. The greater the distance the larger the effort of movement by the pollinator in the landscape. The opposite is also true. Thus, it is possible to have populations that are getting isolated due to the impossibility to reach one another. One explanation for this isolation can be that there exists too many agriculture fields that the pollinator cannot cross, since they amount to hostile environments.

The *diversity of habitat types* is an important aspect of the system because it may favor viable populations to exist. In other words, it means that the more diverse the habitats in the system, the larger the diversity of floral resources for the pollinators. Floral resources are equal to food resources. Thus, in the long term, it is expected that the diversity of habitat types affects the management of viable populations of pollinators. Just as in a chain reaction, if a pollinator population grows then their movement in the landscape will also grow. This may lead towards stability of the pollination services at the time scale of human action in the landscape.

3 MECHANISTIC EXPLANATION

Mechanisms have played an undeniable role in the history of science, which evidently extends to the present day, especially in biology. Notwithstanding, contemporary biology no longer uses the word 'mechanisms' with a literal connotation applied to living organisms and biological systems. Instead, mechanisms are currently used in contexts related to causal relations. The utilization of mechanism in the context of mechanistic explanation can be, therefore, embedded in Salmon's causal-mechanical notion of scientific explanation. Even though Salmon (1998:8) did not insist "that all scientific explanations are causal", he still maintained "that knowledge of causal relations enables us to explain a vast range of natural phenomena, and that such explanations yield understanding of the world and what transpires within it". The main features of the causal-mechanical notion in scientific explanation were already exposed in Chapter 1 (Sect.1.1.1), while its implications for scientific understanding were addressed in Section 1.2. Thus, this section is only dedicated to expose the main framework of mechanistic explanation and some examples of its use, throughout the sciences.

At this moment it is really important to note that this section does not aim to present the complete theoretical framework of mechanistic explanation and, also, that it does not aim to do it accordingly to its historical construction. This is justified by the following reasons. First, the new mechanistic philosophy of science is still at its beginnings, with its theoretical framework still in development and being revisited constantly. And second, the theoretical construct of mechanistic explanation had a purpose to be in this thesis. Its framework was combined with theories in ecology in order to derive heuristics that would guide the development of an explicative model of the bees' pollination service in agricultural systems. These two reasons make it difficult or impossible to be fully aware of all the continuous changes within the field while these same principles are being applied during scientific practice. Therefore, only major ideas are presented in this section, in a non-chronological way, in an attempt to accommodate the core discussions that emerged simultaneously throughout the development of this field.

This chapter is organized as follows. Section 3.1 brings some disambiguation on the semantic aspects of mechanisms. Section 3.2 presents major ideas concerning mechanistic explanation that were used in the construction of the heuristics set[9].

[9] Section 3.2 will give a very brief overview of some issues regarding mechanistic explanation. Notwithstanding Chapter 4 will bring extended discussions on the mechanistic framework behind each heuristics, with a deeper analysis of their content.

3.1 Mechanism what? The semantic fragmentation of mechanism

"Mechanism" is a common word used in the sciences, since for many fields what counts as a satisfactory explanation usually requires providing a description of a mechanism. In this sense much of the practice of science, in an historical account, can be understood in terms of the discovery and description of mechanisms (MACHAMER, DARDEN & CRAVER 2000).

In the biological sciences, the concept of "mechanism" is fundamental to an adequate philosophical understanding of some issues, especially in molecular biology (BECHTEL & RICHARDSON [1993] 2010, KAUFFMAN 1971), but not only in this field. Wimsatt (1972:67) defends the idea that "in biology several scientists perceive their work as explaining phenomena by means of identifying mechanism". But there are disagreements about this idea, since authors like Schaffner (1993:278), for instance, claims that "mechanism" is a term that should be avoided.

Despite the fact the term "mechanism" has been used in different times and places in the sciences and in the philosophy of science, there is still no consensus about what a mechanism is. Table B provides some examples of distinct definitions of mechanisms that are, in one way or another, attached to mechanistic explanation.

Table B: Definitions of mechanisms developed by different authors.

Author(s)	Mechanism's definition
Glennan (1996)	Mechanism is a behavior of complex systems that produce such behavior through the interaction of a number of parts. These interactions may be characterized as relative, invariant and direct generalizations.
Machamer, Darden & Craver (2000)	Mechanisms are entities and activities organized in such a way that they are product of regular changes from start to set-up to finish or terminate condition.
Bechtel & Abrahamsen (2005)	A mechanism is a structure that realizes a function in virtue of its component parts, operational components, and organizations. The functioning of a mechanism is responsible for one or more phenomena.
Pickett, Kolasa & Jones (2007)	The term "mechanism" in ecology connotes an interaction that is nested within the entity or system to be explained. A mechanism is, therefore, one sort of cause.
Illari & Williamson (2012)	The mechanism of a phenomenon is composed by entities and activities organized in such a way that are responsible for the phenomenon.
Nunes-Neto *et al.* (2013)	Mechanisms are types of theoretical models, constructed from a hierarchical perspective.

Source: Elaborated by the author.

What counts as mechanisms in science has developed over time and presumably will continue to do so (MACHAMER, DARDEN & CRAVER 2000). Notwithstanding, Nicholson

(2012) distinguishes and characterizes three different meanings and uses of mechanisms in the history of biology: machine mechanism, mechanicism, and causal mechanism. “The *machine mechanism* notion was traditionally used by biologists to describe machine-like systems. It has been applied to stables sets of interacting parts arranged in such a way that their combined operation results in predetermined outcomes”. Its etymological roots are the closest to the Latin *machine* and the Greek *mechane*, meaning ‘machine’ or ‘mechanical contrivance’. *Mechanicism* comprises the idea that living organisms can be treated as machines. Finally, *causal mechanisms* display the step-by-step of causal processes that give rise to phenomena.

Nicholson (2012) highlights that mechanistic philosophy is concerned with the characterization of machine mechanism and refers to the ontological and epistemological commitments of mechanicism. The confusion, for him, is that philosophers of science usually adopt the term ‘mechanistic’ to refer to explanations that are related to causal mechanism, which has nothing to do with mechanicism. And this is where the mechanismic program enters, Nicholson suggests that the term “mechanistic” should be avoided whenever talking about causal mechanisms, because mechanismic, just as causal mechanisms, is better understood as a heuristic explanatory tool, not as real things in nature. Therefore the mechanismic program would be concerned only with causal mechanisms with no commitments with mechanicism. Even though this suggestion attempt to clarify these distinctions, in this thesis we will use mechanistic explanation as regarding mechanism with causal relations with no ontological commitment to mechanicism.

It is worthy claiming that not all scientists look for mechanisms and not all explanations are descriptions of mechanisms (MACHAMER, DARDEN & CRAVER 2000). Biology, for example, is a wide field where scientific explanations surpass a range, from descriptive mechanism to comparative reasoning, to the construction of historical narratives.

The research proposal of this thesis started aligned with an inclination towards Illari & Williamson’s (2012) definition. In spite of this, by the time the ecologist engaged in the project and created his conceptual framework, he adopted Nunes-Neto and colleagues’ (2013) definition. In spite of this, we also agree with Machamer, Darden and Craver’s (2000) and Nicholson’s (2012, 2014) ideas that thinking about mechanisms, when not embedded in a reductionist perspective, and when used as metaphors, might help illuminate aspects of discovery, scientific change as well as address many problems in philosophy of science. Even though Nicholson’s effort in identifying the different usages of the term “mechanism” is of paramount importance, this thesis does not embrace the axiom ‘mechanismic’ only because the heuristic building was solely discussed within mainstream mechanistic literature.

3.2 Mechanistic explanation and its framework

Even though the theoretical roots of mechanistic explanation go back to causal-mechanical reasoning in Salmon (1984, 1998) (see Sect. 1.1.1), the work of Machamer, Darden & Craver (2000, hereafter MDC) '*Thinking about mechanisms'* is usually granted as the ground zero for the new mechanistic philosophy of science. These authors defended that mechanistic thought may provide a new approach to address some major philosophical issues such as causality, laws, explanation, reduction, and scientific change.

MDC (2000:3) regard mechanisms as "entities and activities organized such that they are product of regular changes from start or set-up to finish or termination conditions". The goal of a mechanism is, thus, to explain how a phenomenon succeeds or how some processes operates. A mechanism for MDC must have an *initial condition* (*set-up condition*) and a *terminal condition* (*termination condition*) (as well as intermediate stages), and a mechanistic explanation, accordingly, ought to describe these aspects of the phenomena.

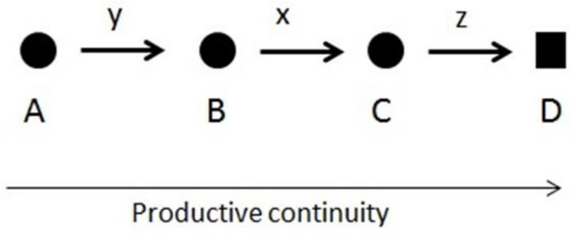
In more detail, MDC describe mechanisms as composed of *entities* with their own properties and a*ctivities* with their own functions. Hence, the activities are intrinsically related to the properties of the entities, since they produce the action. The entities are the things involved in the activities and therefore have specific types of properties. The activities are the producers, responsible for change.

Notice that, for these authors, some key points are *organization, regular changes, set-up,* and *termination conditions*. The *organization* and the dynamics of the entities and activities will establish the path through which the phenomenon will be produced. Entities must be specifically situated, structured, and oriented. The activities in which they participate must be coordinated temporally, involving a temporal order, rate, and duration.

Concerning *regular changes,* "mechanisms are regular in that they work always or for the most part in the same way under the same conditions" (MACHAMER, DARDEN & CRAVER 2000:3). Two important aspects related to this issue are *productive continuity* and *intelligibility*. The first one is the regularity *per se* of the mechanism to run from the beginning towards an end, along the stages, when free from adversities. This regularity will establish a *set-up condition* and a *termination condition*. The second one, the intelligibility of the mechanism, results from the productive continuity along its stages (Figure IV).

Taking into account previous information, to describe the mechanism of a phenomenon is, thus, to reveal how the termination condition is caused by the initial (set-up) and intermediate conditions, in an organized and constant way. Figures V and VI represent mechanisms of biochemical processes, used by MDC (2000:9-10) to exemplify their ideas. The first diagram is a two-dimensional spatial representation of chemical synapses. The second one represents the mechanism of a single activity of these synapses – the depolarization.

Figure IV: Schematic representation of a mechanism according to MDC. A, B, and C are the components of the mechanism. y, x, and z are the activities carried out by the components. A represents the set-up conditions, and D represents the termination condition, in other words, the product of the chain of activities. The productive continuity between the components will provide intelligibility to the mechanism.

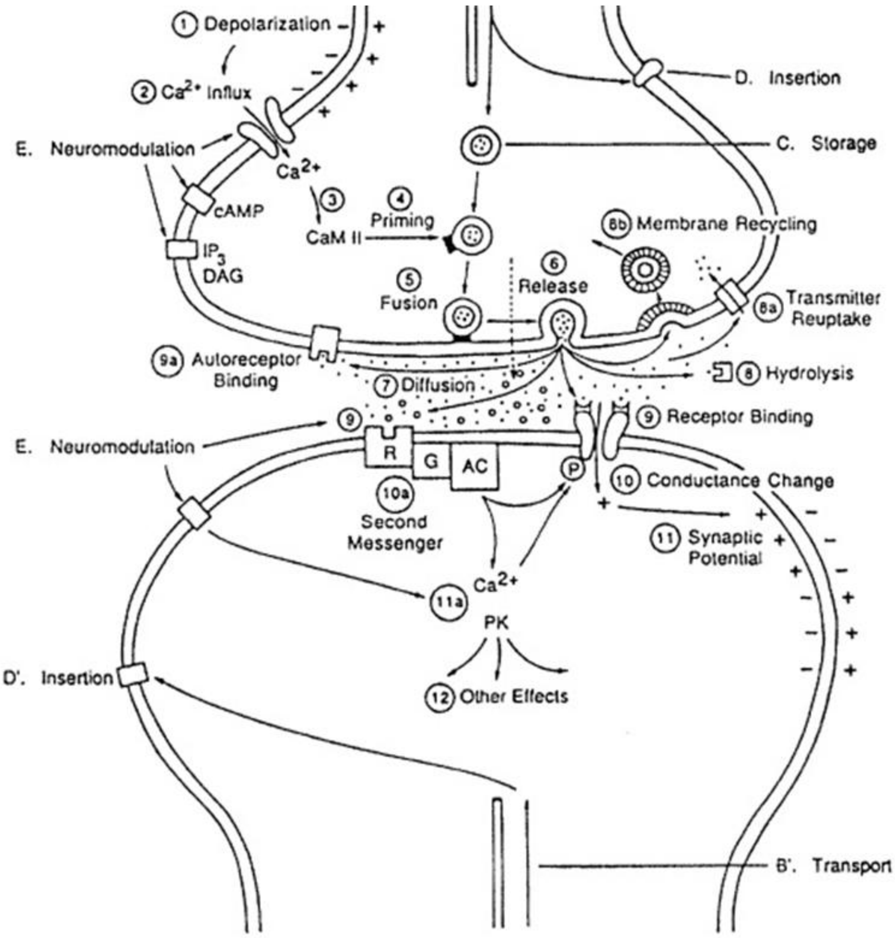


Source: Elaborated by the author.

Figure V contains the elements and activities of the process. The elements include, for example, cell membrane, vesicles, microtubules, molecules, and ions. The activities are represented, for by the actions of biosynthesis, transport, depolarization, insertion, storage, recycling, priming, diffusion, and modulation. The mechanism happens with the neurons that are polarized in resting state. The fluid inside the cell membrane is negatively charged with respect to the fluid outside of the cell. The depolarization is a positive change in the membrane potential: neurons depolarize when sodium (Na+) channels in the membrane open, allowing Na+ to move into the cell by diffusion and electrical attraction. The resulting changes in ion distribution make the intracellular fluid progressively less negative and, eventually, more positive than extracellular fluid (MDC 2000).

Figure VI represents the mechanism of depolarization involving the Na+ channel (through which Na+ ions get inside the neuronal membrane). The three panels of the Figure (top-to-bottom) represent the set-up condition, intermediate activities and termination condition of the mechanism. In the depolarization mechanism, the termination condition (at the bottom panel) is considered to be the increase in membrane voltage, in other words, the depolarization of the axon terminal illustrated by the Na+ channels lining up against the intracellular membrane surface. The intermediate activities (at the central panel) are presaged by the set-up conditions, and are represented by the spreading depolarization from the axonal action potential that (1) repels the positive charges in the alpha helix voltage gates, and (2) rotates their central axis and opens a channel in the membrane. The resulting conformation of the protein (3) makes the channel selective for Na+. As result, (4) Na+ ions move through the pore and into the cell. This increase in intracellular Na+ depolarizes the axon terminal (MDC 2000).

Figure V: Mechanism of chemical synapses in a neuronal cell.



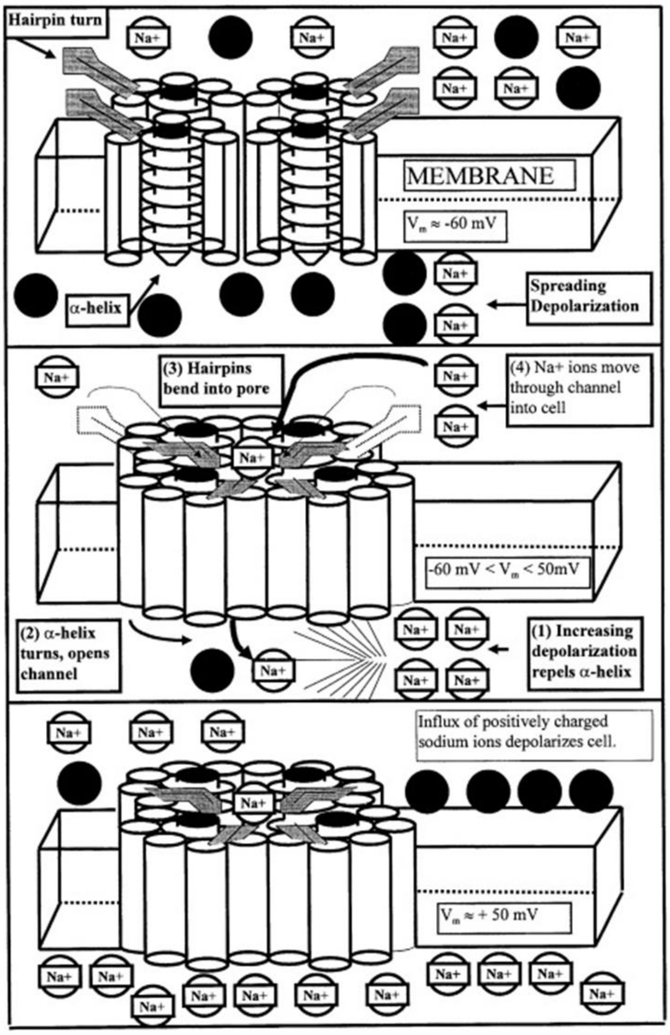
Source: Machamer, Darden and Craver (2000:8-9) extracted the images from Gordon M. Sheperd, *Neurobiology*, 3/e; ©1994 by Oxford Press, Inc., and Hall, Zach W (ed.) (1992), *An introduction to molecular neurobiology*. Sunderland, MA: Sinauer Associates.

Unlike MDC, Craver & Bechtel (2006:469) do not offer an explicit definition for mechanism. Notwithstanding, they suggest that every model of a mechanism possesses four aspects: a phenomenal aspect, a componential aspect, a causal aspect, and an organizational aspect (Figure VII).

The *phenomenal aspect* concerns the phenomenon in question: "mechanisms do things; they are the mechanisms *of* the thing they *do*. […] There are no mechanisms simpliciter –

only mechanisms *for* phenomena" (Craver & Bechtel 2006:469). The *componential aspect* relates to the components or the working parts of the mechanism, but not all components, only those relevant to the phenomenon at stake. The *causal aspect* relays on the activities exhibited by the components of the mechanisms. As they are activities, they are usually exposed as verbs. The *organizational aspect* is the temporal (order, rates, durations, and frequencies) and spatial structure (locations, shapes, sizes, orientations, connections, and boundaries) in which the components and activities of the mechanism operate. There are different patterns of mechanistic organization: feed-forward or push-pull systems, feedback or parallel connections.

Figure VI: mechanism of depolarization involving the Na+ channel.



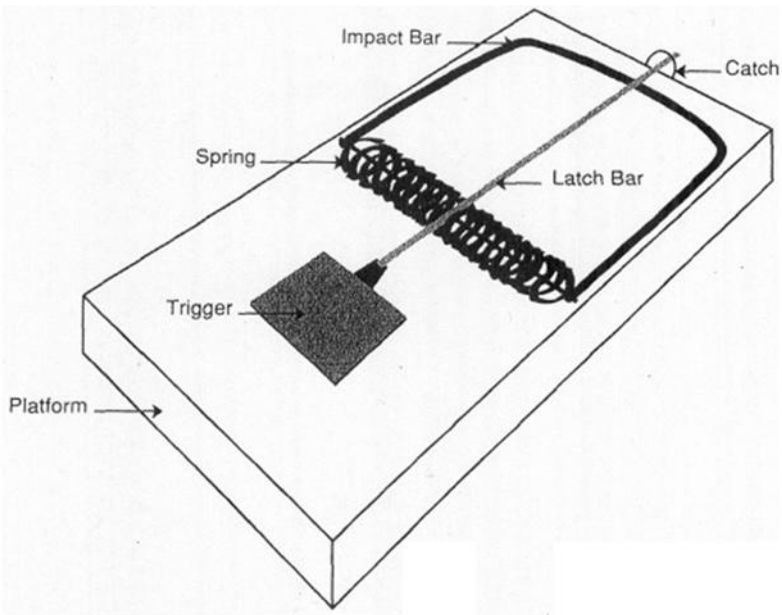
Source: Machamer, Darden and Craver (2000:12) extracted the images from Gordon M. Sheperd, *Neurobiology,* 3/e; ©1994 by Oxford Press, Inc., and Hall, Zach W (ed.) (1992), *An introduction to molecular neurobiology.* Sunderland, MA: Sinauer Associates.

The authors utilize a common mousetrap to explain their ideas (Figure VII). The phenomenal aspect of a mousetrap is to trap mice. It possesses six components: trigger, spring, latch bar, catch, impact bar, and platform. All the components have properties that will influence directly or indirectly the activities. For instance, the rigidity of the impact bar and the tension of the spring offer a direct stimulus for the phenomenon to happen. Indirectly speaking, the platform does not influence the event but offer a substrate for it. In this aspect and in spite of their differences, Craver & Bechtel are in agreement with MDC:

> [a]mong relevant entities and properties, some are crucial for showing how the next step will go. The bulk of the features in the set-up (spatial, structural, and otherwise) are not inputs into the mechanism but are parts of the mechanism. They are crucial for showing what comes next; thus we avoid talk of "inputs", "outputs," and "state changes" in favor of "set-up conditions," "termination conditions," and "intermediate stages" of entities and activities (MDC 2000:11).

The causal aspect and the organizational aspect are intimately related such that when the mechanisms are loaded, the parts are connected to one another. For instance, in the mousetrap, the trigger must be located with respect to the catch such that any pressure on the trigger moves the trigger bar to dislodge the catch (CRAVER & BECHTEL 2006:470).

Figure VII: elements of the mechanism mousetrap.



Source: Extracted from Craver & Bechtel (2006).

The work of another author from the new mechanistic philosophy of science, Stuart Glennan, is different from those quoted above, as his discourse permeates causal matters, laws, and generalizations, as explicit in his first definition of mechanism: "a mechanism underlying a behavior is a complex system which produces that behavior by the interaction of a number of parts according to direct causal laws" (GLENNAN 1996:52).

The core of his discussion concerns the idea that the mechanistic account is not undermined by the lack of a fundamental physical causation. This may appear contradictory when looking at his own definition of a mechanism, but he asserts so because "mechanisms provide an epistemologically unproblematic way to explain the necessity which is often taken to distinguish laws from other generalizations" (GLENNAN 1996:49). Associated with this idea, the author develops the notions of mechanisms as *causal nexus* and mechanisms as *complex systems* (GLENNAN 2002:S343).

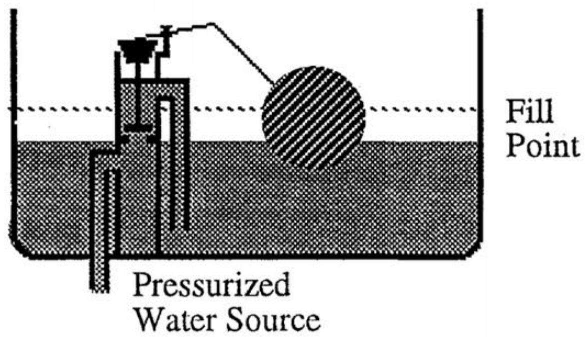
Mechanisms as causal nexus are extracted from Salmon's work on causal-mechanical explanation. Salmon defines causal nexus as a network of interacting causal processes. Mechanisms as complex systems are in turn extracted from the works of Wimsatt (1994), Bechtel & Richardson ([1993] 2010), and Machamer, Darden & Craver (2000). Regarding this idea, Glennan develops a more elaborate definition as follows:

> A mechanism for a behavior is a complex system that produces that behavior by the interaction of a number of parts, where the interactions between parts can be characterized by direct, invariant, change-relating generalizations (GLENNAN 2002:S344).

Another important issue for Glennan is behavior. The mechanism's boundaries, its parts and its interactions are only possible to identify if the mechanism behavior is previously known. It is important to note that Glennan sometimes uses the term 'behavior' to refer to properties, sometimes to activities, sometimes to phenomena, and sometimes to laws. Perhaps it is possible to assign this disparity because of his perception of mechanisms as complex systems, where a mechanism may possess different other mechanisms within, underlying its behavior, as he beautifully calls the *polymorphous behavior of complex systems* (GLENNAN 1996). The author uses two simple systems to demonstrate how they can be analyzed in terms of his definition of mechanism: a float valve and a voltage switch (Figures VIII and IX). In turn, to exemplify the idea of complex systems he uses the human body.

The float valve (Figure VIII) is a mechanism that regulates the water level in a tank. According to Glennan's definition of mechanism, the purpose of the float valve is to regulate the water level while the behavior of the mechanism is the maintenance of the water level in the tank. It is possible to identify its parts: tank, valve, pressurized water source, lever and float. The causal interaction between the parts in the mechanism is represented by the float attached to a lever; this lever opens and closes an intake valve. Whenever the lever is down, the intake valve is open and allows water to fill the tank. When the lever is raised to a certain point, the intake valve closes, stopping the flow of water. The float is heavy enough that in the absence of water it will pull the lever down, opening the intake valve (GLENNAN 1996).

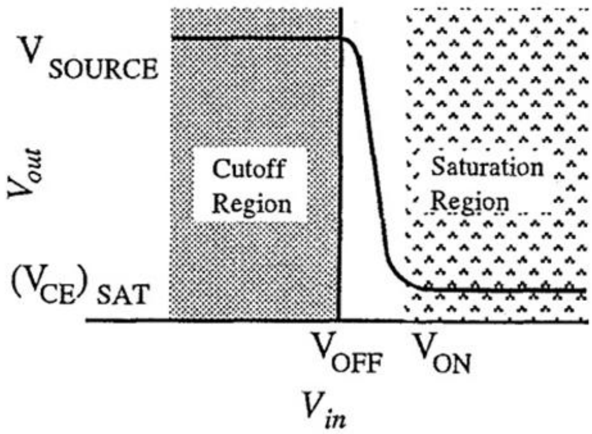
Figure VIII: A float valve as a mechanism.



Source: extracted from Glennan (1996).

The second example is a voltage switch (Figure IX). This example is really interesting because this mechanism is not triggered by a mechanical switch, but by an electrical impulse.

Figure IX: A voltage switch.



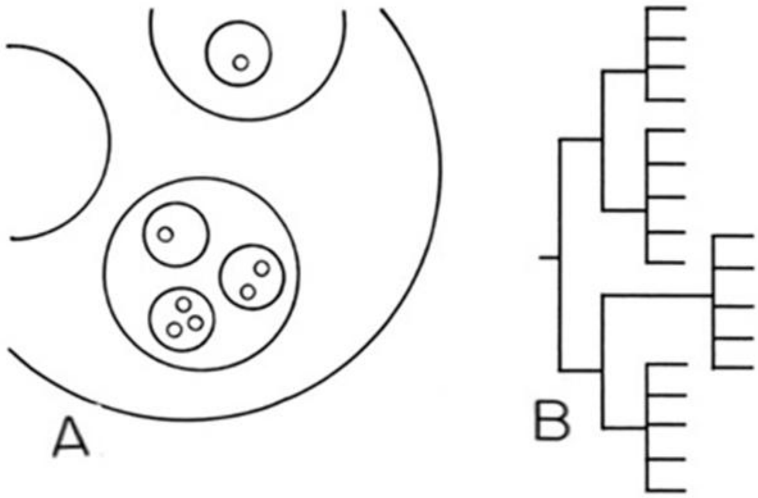
Source: Extracted from Glennan (1996).

The behavior of this mechanism is the variation of the input voltage V_{in} to the output voltage V_{out}. Its parts are the junction transistor with three terminals (the base, the emitter, and the collector), two resistors (bias resistor and load resistor), and the terminals of a battery (positive voltage source rail and a ground). The property and interaction of the transistors is given by the fluctuation on the saturation voltage (VCE). This circuit is a type of current valve, when Vin ≤ VOFF (*i.e.*, voltage entering the base is negative), the valve is closed and no current passes from the emitter to the collector. When Vin ≥ VON (*i.e.*, voltage entering the base is above a small positive value), the valve is open and current passes from the emitter to the collector. When VOFF < Vin < VON, the valve is part way open, allowing restricted current flow between the emitter and the collector (GLENNAN 1996:60).

The example Glennan uses for mechanisms as complex systems is the human body, in particular, two subsystems: the cardiovascular and the respiratory systems. These systems possess multiple mechanisms involved, say, in pumping blood, inhaling oxygen, and exhaling carbon-dioxide. If one considers the behavior of oxygenating the blood, for instance, it is possible to consider both systems as components of a sole mechanism even though they divide the body into different parts. The parts of the cardiovascular system are heart, veins, arteries, capillaries, etc. And the parts of the respiratory system are lungs, diaphragm, windpipe, mouth, etc. Glennan states that the properties of both systems overlap and their boundaries are only delimited according to the behavior in question.

Mechanisms as complex systems were formerly discussed by Wimsatt (1994) and posteriorly by Glennan (1996, 2002), MDC Craver (2000), Craver (2001; 2007), Bechtel & Richardson ([1993] 2010), among other authors. These treatments, which harbor earlier propositions of systems as hierarchical levels (SALTHE 1985) (Figure X), provide the basis for the elaboration of the heuristic "hierarchical structure" (Sect. 4.1.3) in our work.

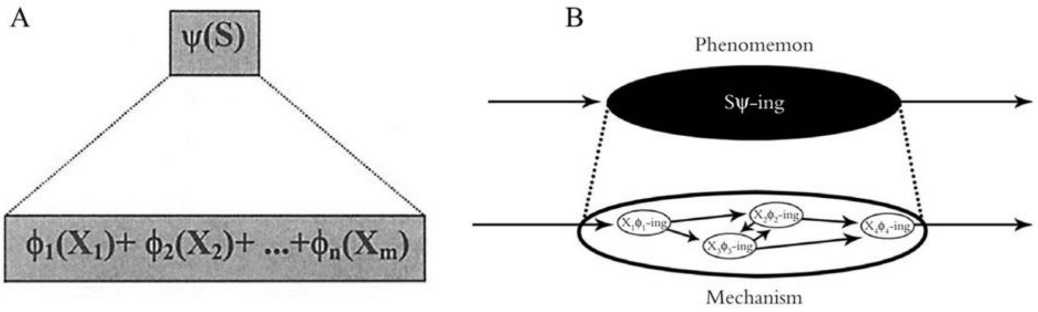
Figure X: Salthe's diagrammatic views of hierarchical structures: (a) compositional hierarchy of nested entities; (b) control hierarchy.



Source: modified from Salthe (1985:10).

The most well-known scheme representing mechanisms with hierarchies is exposed by Craver (2001, 2002, 2007) (Figure XI). According to this author, "mechanisms are entities and activities organized such that they exhibit the *explanandum* phenomenon" (CRAVER 2007:6). Craver's analysis of hierarchies is focused on the nomological functions of the mechanisms' parts and is basically derived from Cummins' (1975) analysis of role functions. At the top of the schema is the phenomenon to be explained or the behavior, symbolically represented by the Greek letter ψ, while the mechanism of ψ is represented by the letter *S*; therefore, the mechanism of the phenomenon is *S*ψ-ing. At the bottom of the schema or at the lower level are the entities (circles) and the activities (arrows) of *S*ψ-ing. The components entities of *S* are represented by *X* and the activities of the components are represented by Φ. Thus, according to Craver (2007:7) "*S*'s *ψ*-ing is explained by the organization of entities $\{X_1, X_2, \ldots, X_m\}$ and activities $\{\Phi_1, \Phi_2, \ldots, \Phi_n\}$".

Figure XI: Diagrammatic views of hierarchical structures: (a) is a diagrammatic view of Cummins' analysis of role functions; and (b) represents Craver's analysis of role functions derived from Cummins.



Source: extracted from Craver (2001, 2007).

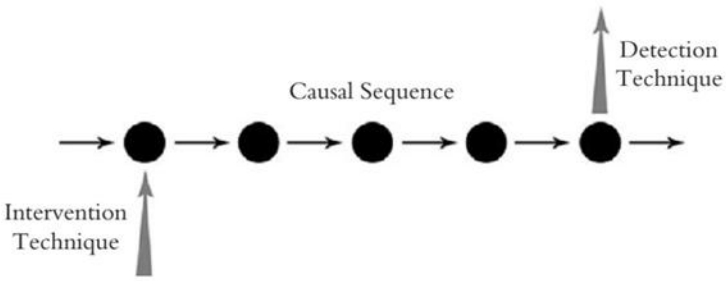
The phenomenon and the mechanism producing it are surrounded by a dotted line which represents their boundaries (Figure XIb). This suggests the idea that both mechanism and phenomenon may be part of an external context. The outside arrows represent influences from the external environment over the phenomenon or over some parts of the mechanism (CRAVER 2007; BECHTEL 2015). This external context relates with the mechanisms' boundaries in our case study and will be considered in the heuristic "external regulatory agents" (Sect. 4.1.8).

For instance, the capacity of the circulatory system (*S*) of distributing nutrients and gases to body tissues (ψ) may be explained by analyzing *S*'s parts (say, X_1 heart, X_2 arteries, X_3 kidneys, and X_4 valves) and their activities (Φ_1 to pump, Φ_2 to convey, Φ_3 to filter, and Φ_4 to regulate the direction of blood flow).

Decomposing mechanisms into their parts for explaining phenomena is facilitated by two strategies that analyze and isolate component functions: *synthetic and analytical methods* (BECHTEL & RICHARDSON [1993] 2010). The analytical method can work, for instance, from an inhibitory experiment that isolates components physically within the system to determine their function. In turn, the same strategy can work from an excitatory experiment that adds a stimulus to a component of the system in order to discover its behavior. The synthetic strategy demands in turn a preliminary hypothesis about the system's organization and operation. Subsequent to this hypothesis, a model is built and empirical testing is realized with the purpose of discovering the behavior of the system. The two strategies are complementary. The first one provides empirical data and the second one provides a theoretical framework that may ground data gathering and analysis.

Craver (2002, 2007) describes a similar approach, the *interlevel expe rimental strategy*, composed by tests of constitutive (or componential) and causal relevancies. These strategies concern excitatory studies, whose interventions in specific parts of the systems may suggest causal relations between the components. This intervention may also indicate which elements are parts of the mechanism and which are not (Figures XII and XIII).

Figure XII: Diagram representing an interlevel experimental strategy of causal relevancy

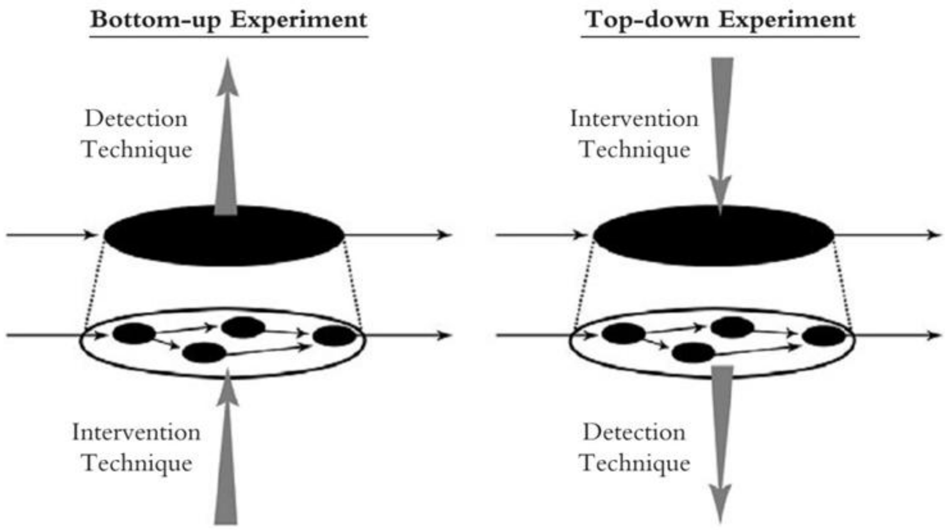


Source: Craver (2007:145).

Every interlevel experimental strategy will possess three basic elements: (i) intervention technique; (ii) causal sequence; and (iii) detection technique (CRAVER 2002). Figure XIII pictures an experiment of causal relevance with a single mechanistic level. Circles and arrows represent components and activities, respectively. The intervention occurs in any variable of a causal sequence to detect any consequences in a downstream variable. Differently, in an interlevel experiment, the intervention and detection techniques are applied and observed at different levels in the mechanistic hierarchy. The intervention may occur in different spots according to two different strategies: the bottom-up experiment and the top-down experiment.

In the bottom-up experiment (Figure XIII left) the intervention will occur with the compositional elements at the level of the mechanism in order to observe changes in the behavior or byproduct at the level of the phenomenon itself. In the top-down experiment the opposite approach will be used, with the interference occurring at the level of the phenomenon in order to detect changes in the composition and activities of the mechanism at a lower level (Figure XIII right). Thus, interlevel experiments verify the correlation between the phenomenon, i.e., the *explanandum*, at a higher level and the components of the mechanism, i.e. the *explanans*, at a lower level (CRAVER 2007:145).

Figure XIII: Diagrams representing two different strategies for interlevel experiments (bottom-up and top-down experiments).



Source: Craver (2007:146).

Darden (2002, 2006) suggests a different alternative to identify and construct mechanism's elements and activities, or to recognize its productive continuity: the schema instantiation and the forward/backward chaining. The first one involves filling roles in an overall mechanism while the second one eliminates gaps using knowledge about types of entities and activities. The second strategy, forward/backward chaining, has two subtypes: one for entities and another for activities. To investigate entities during forward chaining, one may use what is known as the *activity-enabling properties of entities.* This allows one to speculate the kinds of activities with which an entity can engage. Alternatively, there is the *activity consequences*, where one may use knowledge about an activity in the mechanism in order to conjecture the consequences of that activity for both entities and activities. Conversely, in backward chaining, the properties of an entity can provide clues as to the activities that produce it, a sort of an *activity signature* – a property that signals to the researcher the prior occurrence of some activity. Alternatively, during backward chaining, one may find *entity signatures* of activities, that is, properties of activities that provide clues as to what entities in a prior stage may have led to the occurrence of those activities (DARDEN 2006:89).

The strategies proposed by Bechtel & Richardson ([1993] 2010), Craver (2002, 2007) and Darden (2006) provided enough framework for the elaboration of the heuristic "operational component distinction" (Sect. 4.1.5) in this work. This section gives a very brief overview on some issues regarding mechanistic explanation. Chapter Five will bring extended discussions on the mechanistic framework behind each heuristics, with a deeper analysis of their content.

PRELIMINARY CONCLUSIONS

In previous sections we made an effort to give a brief overview of the mechanistic literature and to introduce our case study, the phenomenon to be modeled - the community organization of autochthonous bees and pollination service maintenance in agricultural systems. Both chapters were elaborated to introduce the theoretical framework on which the heuristics were grounded. The specific theoretical construct pertaining to each heuristics, their elaboration and a more extended definition of the elements in the heuristics set will be meticulously detailed in Part II, nonetheless, as the heuristics set emerged as a product from the interdisciplinary collaboration established in this work, its general description will be, for now, exposed in Table C.

Table C: Heuristics set developed in interdisciplinary work engaging ecology and philosophy of science. A brief description is provided for each heuristics.

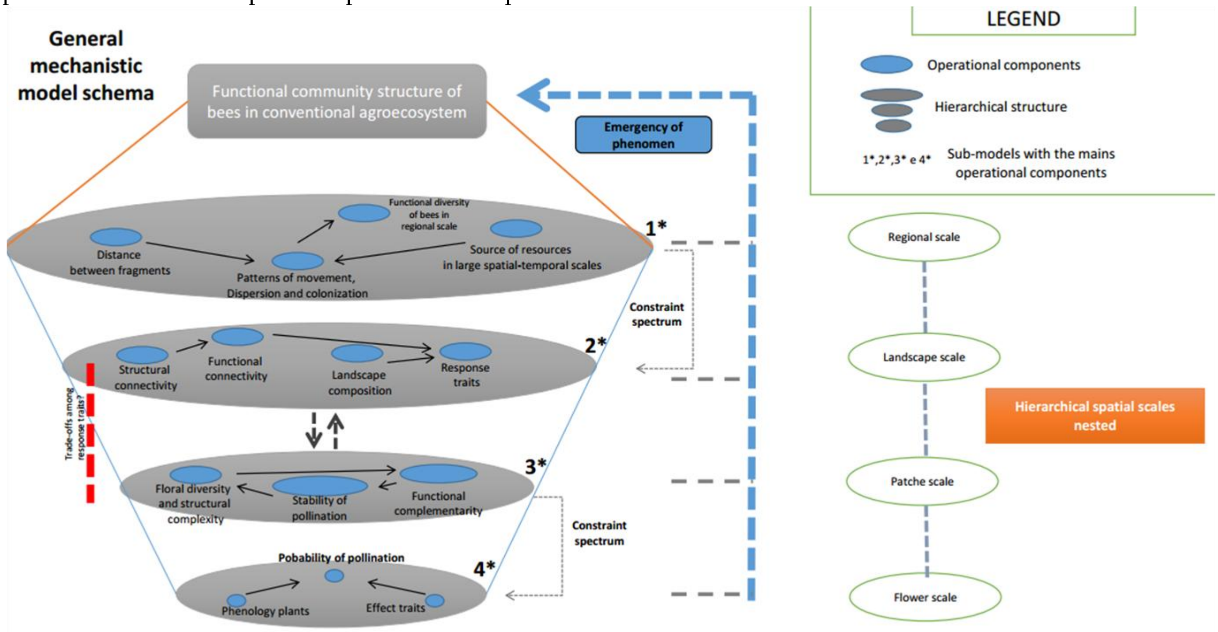
Heuristics	**Brief definition**
Phenomenon characterization	It is the description of the phenomenon to be modeled and what will be considered in its explanation.
Mechanism sketch	It consists of diagrams that aim to establish the relationship between the theoretical frameworks and the phenomena to be explained, in order to construct a model to explain the phenomenon. Two are the most important features of this sketch, its lack of information and its disposable nature. Any mechanism sketch possesses gaps, gray and black boxes, and may be discarded whenever is needed.
Hierarchical structure	It aims to identify and locate the amount of levels in which the mechanism (or mechanisms) is organized and nested in the phenomenon superstructure. This heuristics may enable visualizing the interaction between different spatial and temporal scales.
Enabling conditions	Variables selected as the most relevant in the mechanism that originates the phenomenon. They can be selected by identifying the set-up conditions or via the information already available in the scientific literature.
Operational components distinction	Its goal is to distinguish the components and functions of the enabling conditions within the mechanism and specify the relations and boundaries between those components. If this information is not yet in the theoretical literature, it is highly recommended to carry out procedures of decomposition & localization, forward & backward chaining, and synthetic & analytic strategies to achieve this goal.
External regulatory agents	It is the identification of the variables that are external to the phenomenon but nonetheless exert indirect influences over it. Such influences might be related to boundaries delimitation.
Evidence frequency	It intends to indicate causality between the elements of the enabling conditions according to probabilistic and mechanistic information already

	available in the scientific literature or gathered through procedures of decomposition & localization, forward & backward chaining, and synthetic & analytic strategies.
Cluster determination	It is the determination of cluster nodes by means of graph network. It possesses two distinct purposes: to furnish a solid ground to the operational component distinction by providing elements to ascribe weight to the evidence frequency table; and to grant robustness to the enabling conditions as well as to the hierarchical structure.
Mechanism schema	It is the conceptual model obtained after the use of the heuristics above.
Changing in operational components	It aims to exploit alternative scenarios and predict possible courses of the system under investigation by modifying the operational components.

Source: Elaborated by the authors.

Table C gives a brief description of the heuristics. The application of the heuristics will be analyzed in Sect. 4.1. As a result of the heuristics application, the mechanistic model shown in Figure XIV was developed by the modeler.

Figure XIV: General mechanistic model indicating the main spatial scales of influence on the service of pollination with the respective operational components.



Source: Coutinho: *personal conversation*.

The general mechanistic model created by the modeler clearly expresses some main features of the mechanistic explanation. It possesses components and activities carried out by them (which provide a productive continuity in the mechanism), and a spatial and temporal organization in the form of a hierarchical structure containing four levels. The image on the left side represents the operational components at each level: 1* indicates ecological components and processes that occur at a regional scale and provide the regional pool of species that operate at the more restricted spatial scales; 2* includes aspects of the structure of the landscape that influence the functional composition of the bees through the interaction with certain response traits, which are the traits that condition the response in richness and abundance to these spatial attributes of the landscape; 3* contains structural characteristics of habitat patches that influence the probability of more or less complementarity of traits at this scale, influencing the space-time stability of the pollination service; 4*, the finest scale used in this model, indicates that pollination success will ultimately depend on plant phenological attributes (supply of resources compatible with the needs of bee communities, for example) and effect traits (traits of bees related to the successful transfer of pollen grains).A more detailed analysis of each level of this general mechanistic model will be provided in section 4.1.

As already stated previously, the mechanistic model was discarded at some point of the ecological investigation in order to elaborate a theoretical framework that was regarded by the modeler as apt for explaining the phenomenon (Box 1).

Box 1: description of the framework 'Bee functional diversity in agroecosystems: a theoretical model unifying ecology, mechanistic explanation and complex systems science'.
The study of functional diversity is a more promising way of establishing connections between community structure and the functioning of ecosystems, since the focus of this approach is on the attributes or functional traits of the species (LOREAU 200; DIAZ et al., 2007), which can be related to the probability of these species being found in a given environmental context (response traits) (BARTOLOMEU et al., 2017, RICOTTA & MORETTI 2011), or to the efficiency of these species to act directly on an ecosystem function or service (effect traits) (WOOD et al., 2015). However, in spite of this potential, the current literature on the functional diversity of bees in agricultural systems has some important characteristics that may hinder the advancement of the functional approach, considering bees as biological models and pollination as an ecosystem service. Much of this difficulty is associated with: 1) trade-offs rarely considered in approaches whose recurrent classifications use single response traits; 2) lack of clear definition of function, response and effect traits, leading to a myriad of conclusions without satisfactory explanations about ecological processes and patterns of diversity; 3) rare studies considering multi-trait approaches using appropriate mechanistic explanations that connect processes at multiple spatial scales. This set of evidence motivated us to elaborate a theoretical model that contributes to overcome these difficulties presented in the empirical literature. For this, we discussed the concept of response and effect traits in an organizational perspective of function and how this aspect can improve the choice of functional traits in our analyses; we pointed out the theory of metacommunities and two of its models as promising in the connection between ecological processes and functional diversity of bees in agricultural systems; and, finally, we derived some hypotheses that must be tested in relation to the influence of environmental gradients on different properties of functional diversity. We constructed this model based on a set of heuristics derived from the theory of mechanistic explanation, approaching Ecology to epistemic bases that can help to deal with complex phenomena. The organizational function approach used in this framework (NUNES-NETO, MORENO & EL-HANI 2014) contributed to the more concise delimitation of two important concepts in the study of functional diversity, response traits and effect traits. We define the former as traits that clearly influence the presence of a given biodiversity item (trace member), and this item (which may be one or a group of species) must contribute precisely to the action that influences the flow of matter and energy. Effect traits consist of a measurable attribute, be it morpho-anatomical or behavioral, which has a direct influence on the limiting action on the flow of matter and energy (process) carried out by the item of biodiversity that

have such trait. Given the more precise delimitation of these concepts, we invested in the dialogue with the Philosophy of Mechanistic Explanation in order to elaborate a conceptual model that would explain relationships of measured variables in different spatial scales, considering an agroecosystem in the practice of intensive agriculture practice, and as such variables may potentially influence three distinct functional diversity properties: functional richness, functional divergence, and functional dispersion. The variables listed reflect the degree of structural complexity of the landscape and local vegetation, considering their importance to the occurrence and distribution of bees in these ecological systems. The conception of the model followed a series of stages, being the dialogue with the philosophy of mechanisms fundamental from the delimitation and conception of the phenomenon to be modeled until the derivation of the core hypotheses that emerged from the conceptual model. The operationalization of this dialogue was possible through a set of heuristics that guided decision-making throughout the construction process. Phenomenon characterization was a heuristics that guided the delimitation of the phenomena to be modeled, through a deep immersion in the ecological literature and prospecting of the main conceptual problems and knowledge gaps associated with the study of the diversity of bees in agricultural systems. Then, Enabling conditions was a heuristics that contributed to the identification and selection of the most relevant variables within each hierarchical level of the modeled phenomenon. Such hierarchical levels were considered, taking into account the multiple levels of interference on the phenomenon, being guided by a third heuristics, Hierarchical structure. This hierarchical structure reflected the spatial scales of interest in modeling the ecological phenomenon. Because it is a highly complex phenomenon, we considered the relative importance of the different variables within each level of the hierarchy, identifying in the ecological literature the relations with more evidence frequency, as well as those whose answers still lack empirical investigations, being the Evidence frequency heuristics important in the accomplishment of this step. An inherent difficulty in the study of functional diversity is the choice of dimensions that reflect biologically relevant properties and with different biological meanings, in order to allow a more complete evaluation of the functional profile of the communities. In this sense, the Operational components distinction heuristics was crucial in choosing the three functional diversity properties mentioned above. Following the logic presented above, two other heuristics that were associated with the advance in theoretical knowledge proposed by our model were the Tipology shape of mechanism[10] and Cluster determination. The definition of typology is crucial in understanding the magnitude that certain ecological processes may have in generating patterns of bee functional diversity. This heuristics points to core hypotheses that need empirical evaluation, with great potential to generate advances in the understanding of the relation between functional diversity aspects and pollination service properties in agroecosystems. Given a certain typology of the mechanism, Cluster determination allows us to identify in the relationship network those nodes that would have more connections with their interactors (BECHTEL 2015). It allows identifying and isolating the clusters in order to understand their importance for the occurrence of the phenomenon under study. The use of this heuristic helps to evaluate the hypotheses more tested and with greater empirical support, besides being a way to derive, from the ecological theories that based the conceptual model, new hypotheses with a cohesive core of ecological processes that are relevant to explain different dimensions of functional diversity. Another aspect of paramount importance concerns the design of species as a mosaic of distinct functional traits. These traits may present important trade-offs among them, since they can show opposite tendencies to the intensive use of the land, influencing in the response of indices that consider multi-trait approaches. In this sense, the heuristics External regulatory agents helped us to reflect on the possible trade-offs between functional traits as well as ecological processes at multiple scales could be conceived according to this heuristics, considering the potential that these trade-offs, historically excluded in the explanation of the functional diversity of bees, may have in the elucidation of mechanisms underlying the patterns found in bee communities in agricultural systems. Finally, following the heuristics called Mechanism sketch, we constructed the graphical representation of this conceptual model. At the end of this dialogue effort between the Mechanisms Philosophy and ecological theories, we discussed the implications of this model in the connection with two ecosystem properties (magnitude and stability), focusing on the service of pollination in conventional agricultural systems.
Source: Elaborated by the authors (*personal communication*).

[10] The referred heuristics 'typology of shape mechanism' it is not considered in this thesis as a separated heuristics, once its goal of visualization of the phenomenon structure is diluted in the heuristics 'hierarchical organization' and 'mechanism sketch'

It is possible to return now to the main question of this Part of the thesis: *Can the new mechanistic philosophy of science, by means of a heuristics set, help scientists construct models while doing science in practice?* Yes, from our findings gathered from field notes, meetings recordings and interviews, we can say that the heuristics derived from the new mechanistic philosophy of science were apt to help the scientist engaged in the present interdisciplinary effort to construct models in his scientific practice (as it will be analyzed in more detail in Chapter 4). Even though the mechanistic model was a temporary step, being discarded at some point of the scientist's investigation, it is clear that it played the role of a mediator toward the construction of the explanation presented in Box 1. This also leads us to an interesting point. As it is perceived in his final theoretical framework shown in Box 1, the literature on mechanistic explanation is represented through the heuristics but the pictorial representation of a mechanism was discarded by the modeler. This obliterating action suggests two things: (i) the mechanistic explanation possesses limitations and was not enough to explain this specific phenomenon, and; (ii) the mechanistic explanation and mechanistic model worked as epistemic instruments for the modeler, which mediated between theory, phenomena and theory construction. This is in consonance with Morgan & Morrison's (1999) proposal that models may behave as mediators between theories and realities, but also with Knuutila (2011) and Knuutila & Boon (2011) in that models are epistemic instruments materially embodied and subject to manipulation We can even go a bit further to say that the heuristics themselves also served as mediators among theories, data, scientists and models, playing a prescriptive role in the scientific practice within this interdisciplinary effort.

At this point, the reader might realize that from what was exposed in Part I was not enough to understand what exactly this phenomenon is, how the scientists used the heuristics to construct his model, and how he developed his framework. And the reader is indeed correct. The idea to exhibit Part I in such a way it was only so the reader could put herself in the philosopher's shoe and perceive the scientific practice in the same way as the philosopher in this collaboration did. This is actually really interesting because an approach like this allows highlighting the contrasting notions of science as a product and science as a process. As the reader might already have solved it, Part I of this dissertation reflects science as a product and Part II reflects science as a process. Thus, the doubts not yet clarified will be, hopefully, resolved following the next sections.

PART II

How is scientific understanding achieved during the process of model construction?

INTRODUCTION

Part I of this thesis aimed to answer the question: *can mechanistic explanation help scientists construct models while doing science in practice?* To address this question, it was necessary to create a set of indicative actions that lead to the modelling of the phenomenon. These actions are referred to in this thesis as heuristics. These heuristics were elaborated by our research team based on the mechanistic literature in the philosophy of science and the literature from ecology. The goal was to integrate these theoretical frameworks within an empirical case study in ecology, on the *functional composition of the diversity of autochthonous bees in conventional agricultural systems*, reflecting an interdisciplinary effort. We already have an answer to that question: yes, mechanistic explanation, by means of heuristics, helps scientists construct models while doing science in practice (see Chapter 2 and 3). But, what was perceived during this endeavor was a shift of the explanation construction from a mechanistic to an unificationist position. Considering that biology is a field that grew extremely disunified, as its studies are fragmented in several epistemic cultures, each one with specific terminology, practices, instruments, methodologies, styles of reasoning and so on (LEONELLI 2009), it is not a surprise that the product of the modeler's[11] explanation is an unificationist theory: *bees functional diversity in an agroecosystem – a conceptual model unifying ecology, mechanistic explanation and complex system sciences*[12] (Chapter 3). With regard to explanations, in most fields of biology that deal with [complex] systems, the unificationist conception has become prominent (see WIENS *et al.* 1993, FILOTAS *et al.* 2014), showing that the theories of scientific explanation exposed in Chapter 1 can be applied to ecology. However, regarding the scientific understanding that occurs when explanation is developed, the most adequate notion for this assessment is the contextual theory of scientific understanding, once it considers all the other theories of explanation as conceptual tools for assessing understanding.

Hence, we should now answer the question posed in Part II of this thesis: *how is scientific understanding achieved during the process of model construction?* By this time we already know that the final product of our case study, developed by the modeler, changed

[11] It is worthwhile recalling that the term "modeler" whenever used in this thesis makes reference to the scientist that makes part of our interdisciplinary group. The scientist, more specifically an ecologist, was responsible for applying the heuristics to our case study, in order to create a mechanistic model of the phenomenon of pollination service in agricultural systems. Therefore, the "modeler" is not used as a generic term, as an allusion to a general category of modelers in science, and we are not analyzing a general modeling practice here. On the contrary, our heuristics are anchored to a very specific case study in ecology.

[12] Coutinho (2018:*manuscript*), Chapter 2.

from a mechanistic model to an unificationist conceptual framework (Part I, Preliminary conclusions). To perceive how and why this transition happened we need to unfold the heuristics application. This disclosure will also help us to assess how the modeler understood the explanation he developed. As we already stated in Chapter 1, to unravel the assessment of understanding, the contextual theory of scientific understanding will be confronted with the heuristic theoretical framework built for this case study, and with the modeler's applications and statements about his practice. It is expected that this analysis will help to further enlighten the theory of scientific understanding as well as help scientists perceive their own scientific processes.

Part II will be structured as follows. Chapter 4 exposes the heuristics application and is related with all the previous steps in this thesis: heuristics construction, modeler's statements, contextual theory of scientific understanding, mechanistic explanation and ecological framework. Chapter 5 intends to give a step further in the appraisal of scientific understanding by elaborating on a model of degrees of understanding.

4 ASSESSING SCIENTIFIC UNDERSTANDING: heuristics as epistemic tools

Mechanistic explanation, as discussed above (Sect.3.2), has its main foundation in Salmon's notions of understanding and explanation. According to Salmon, the goal of scientific understanding is to produce explanation by means of exposing the causal events responsible for the phenomenon. Therefore, this thesis begins with the idea that a phenomenon can be explained by means of a mechanistic model. Thus, the question is: how is the understanding of a mechanistic model (and, consequently, explanation) achieved?

To answer this question we will introduce heuristics construction and heuristics applications as the scaffolding required to elaborate such an explanation. The heuristics construction was briefly summarized in table C (Part I) while its application was assessed by means of an analysis of the ecological model constructed as well as of the modeler's statements about their usage. The heuristics construction exhibited prescriptive features for the elaboration of the *explanandum* and *explanans* while the heuristics application exhibited descriptive features suggesting how the understanding (of the *explanandum* and the *explanans)* was achieved by the modeler.

The goal of this chapter is to show how the heuristics were applied and modified by the modeler, according to both needs related to the description and explanation of the phenomenon, and his scientific practice. Thus, the next sections will concern mainly how the heuristics were applied by the modeler rather than dealing with examples of a general heuristic practice extracted from the literature (as this was already made in chapters 1 and 3). As this was a continuous four-years work, the information resulting from the applications of the heuristics was continuously revised and modified. On the one hand, the heuristics were developed on the basis of theoretical literature and then applied to the case study. On the other, the insights of the case study were also used to refine and reformulate the details of the heuristics. So, the heuristics framework informed scientific practice but scientific practice also informed the heuristics framework (Figure I). Thus, the heuristics construction and application showed that a parcel of the literature on mechanistic explanation did not pragmatically fit in our case study. This suggests that the identification, reconstruction and understanding of mechanisms in complex ecological systems might be a little bit more intuitive than the steps usually suggested in mechanistic literature. This could be one of the reasons for the diagrams and models presented in the next sections differ so much from the final theory presented in the Preliminary conclusions of Part I (Box 1). Thus, the heuristics worked in this research as epistemic instruments, or conceptual tools, for the modeler to grasp the ecological phenomenon at stake. This also indicates that the contextual theory of scientific understanding fits better into the proposal to assess understanding achievement.

For the understanding assessment, I will use the intelligibility standards from the contextual theory of scientific understanding, since this theory considers scientific practice as content- and context-dependent. But, as this theory also treats scientific practice in its historical context, an additional feature I want to deal with concerns to what extent can the contextual theory of scientific understanding be also applied to contemporary scientific practice.

This chapter will expose the heuristics, followed by their brief description, their theoretical framework and their application by the modeler (whenever this information was available). Although this process may appear to be a series of sequential steps, this is not true of how the process has indeed occurred. Most of the time, some heuristics were developed and applied simultaneously. For example, when the modeler was drawing the phenomenon structure he was at the same time thinking about the very enabling conditions that allow such structure to exist. Every time he drew a different structure he also reflected on his phenomenon characterization, and so on. The order in which the heuristics are presented here follows what I perceived to be the most important steps during the explanation construction. First, everything starts with the modeler presenting what it is to be modeled. Second, the question becomes what are the components and elements that enables this phenomenon to exist? Third, what are the causal connections between those elements? Fourth, at what scales of this system these connections happen, allowing the phenomenon to emerge? And so on. After answering these questions, the modeler must evaluate: is the phenomenon characterized in the same way or does it need to be narrowed or even modified? Albeit it is a hard task to identify the heuristics in the scientific practice, it is important to present them individually, so that we can understand the role each of them had in the model construction and in the understanding process.

The assessment of such tools for scientific understanding was only possible when the pragmatic aspects of the heuristics were disclosed (figure I). Thus, in the next pages I will elaborate on how these heuristics functioned as epistemic tools for the assessment of understanding. For that I will consider the conceptual tools of intelligibility as exposed by the contextual theory of understanding in comparison with the modeler's practice of model building plus his statements about the heuristics. I believe that by doing so it will be possible to ascertain the value the heuristics had to the modeler, both as inferred from the model he constructed and as expressed by the scientist himself when talking about the heuristics.

4.1 Heuristics as instruments

4.1.1 Phenomenon Characterization

It is the description of the phenomenon to be modeled and what will be considered in the explanation of the phenomenon.

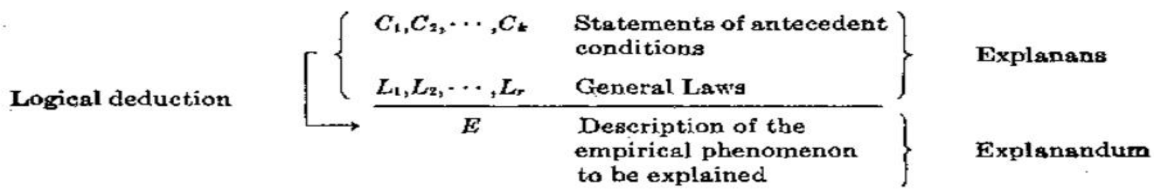
A common starting point in the literature on mechanisms is that the phenomenon is a byproduct (CRAVER & DARDEN 2013:54) or behavior (GLENNAN 2002:*passim*) that emerges from mechanisms. Therefore, a characterization of the phenomenon is needed to unravel underlying mechanisms responsible for it (as a mechanism is always a mechanism of a given phenomenon). Such description needs to be suitable to delineate possible spaces of action of a mechanism as well as its boundaries. These spaces will be framed according to the explanation of the phenomenon. The construction of the hypothesis space is possible because certain phenomena are suggestive of possible mechanisms (CRAVER & DARDEN 2013:52). At a first impression, these assertions may sound rather tautological, but it is important to have this idea transparent because “to describe a phenomenon is to characterize it in the language of a given field and to implicitly call up the host of explanatory concepts” (CRAVER & DARDEN 2013:52).

One implication of this is that elements, activities and functions will only be included in the description if they are relevant to the phenomenon itself. This relevance concerns all entities, activities, and organizational features that directly or indirectly enable the phenomenon (CRAVER & BECHTEL 2006). The characterization of the phenomenon is not an easy task, easily made in one or two paragraphs, and some aspects (possible steps) might not be adequate for the phenomenon at stake in this project, for instance, the synthetic and analytic strategies proposed by Bechtel & Richardson ([1993] 2010). These strategies are inappropriate for our case study because all the empirical data needed for the modeling had already been collected and/or was already provided by the ecological and biological literature. It is possible, though, to make a previous assertion that some aspects of the phenomenon will only be characterized along with the applications of the heuristics.

An interesting alternative that might be more adequate with regard to the ecological phenomenon under discussion, a little bit thought-provoking though, is to incorporate some features of Hempel & Oppenheim's (1948) deductive-nomological (DN) model into this heuristics. To motivate this suggestion, allow me to remind that one subtle aim of this thesis is to challenge traditional epistemological postures by building a communicative bridge between distinct fields such as ecology and philosophy. For this purpose, let's briefly return to the DN model[13].

According to Hempel & Oppenheim (1948:§3,136-7), an explanation of a phenomenon must possess "two major constituents, the *explanandum* and the *explanans*" (Figure XV). By the *explanandum*, they understand the sentence describing the phenomenon to be explained (not the phenomenon itself). The *explanans*, in turn, was conceived as the class of sentences which are adduced to account for the phenomenon. The *explanans* contains statements of two kinds: antecedent conditions and general laws. The antecedent conditions are a set of sentences concerning certain conditions realized prior to, or at the same time as, the phenomenon (C_1, C_2, …, C_k). The second statement articulates a set of sentences (L_1, L_2, … L_r) that represents general laws. Thus, the explanation corresponds to the general laws in virtue of what the antecedent conditions exist.

Figure XV: Hempel & Oppenheim's schema representing the logic components of the explanation of a phenomenon.



Source: Hempel & Oppenheim (1948).

For Hempel & Oppenheim, when an explanation is proposed it must satisfy some *conditions of adequacy*. These conditions are divided into logical (R1-R3) and empirical (R4):

(R1) the *explanandum* must be a logical consequence of the *explanans*.

[13] The selected slice of this model includes the *explanans* and *explanandum*. Although they were utilized in subsequent models, for instance, IS (inductive-statistical model), SR (statistical-relevance model), CM (causal-mechanical model), they were initially proposed by Hempel & Oppenheim (1948) when introducing the DN model. It is crucial to notice that the problems of the models mentioned above were exhaustively discussed in a large literature (*e.g.* KIM 1962; HEMPEL 1965; SALMON 1965, 1971, 1978, 1984; VAN FRASSEN 1980), and it is not the goal of this section to point toward these problems. Notwithstanding it is important to have a minimum recap to understand this slice properly.

(R2) the *explanans* must contain general laws.

(R3) the *explanans* must have an empirical context.

(R4) the sentences constituting the *explanans* must be true.

These four conditions fit, according to them, both scientific explanation and prediction. The difference between them would be of a pragmatic character (*ibidem*:138). If *E* (=description of the empirical phenomenon) is given prior to the statements (C_1, C_2, … C_k, L_1, L_2, … L_r), then the statements explain the phenomenon given by *E*. If those statements are given prior to *E*, then the statements predict the phenomenon described by *E*.

Even though the general principles of Hempel & Oppenheim's model were applied to other sciences, their characterizations of scientific explanation were based exclusively on cases taken from physical sciences and a few examples from chemistry, and perhaps that's why they related their model to causal explanation because it was applied to push-pull systems. This justifies their claim of predictability as symmetrical with explanation through general laws.

Laws (or law-like statements), causal events, predictability are crucial to some explanations (such as those of the action potential, the citric acid cycle, the edge-detection in vision, etc.) but rather dubious for some mechanistic explanations and controversial in epistemology. In contemporary scientific research, it is already assumed that mechanistic explanation based exclusively on canonical examples is insufficient to explain certain phenomena (ZEDNIK 2015), for instance, when dealing with complex systems.

Another interesting element that will add to this heuristics is the [qualitative] *explananda*, which concern unique events situated in the past. This does not preclude that these events be explanatory, but indicates that they likely require a different style of explaining, typically based on narratives (BRAILLARD & MALATERRE 2015:10). Due to the evolutionary aspects of living systems, historical narratives have a strong explanatory force in biology, which does not depend much on particular circumstances. Thus, the *qualitative explananda* will correspond to those evolutionary characteristics that enable, directly or indirectly; the phenomena (see the heuristics 'enabling conditions', Sect. 4.1.4).

At this point, the idea of the heuristics 'phenomenon characterization' may be reformulated in order to describe the *explanans* and *explanandum*. For instance, at a first moment one of the goals of this heuristics was to point out the elements that would explain the phenomenon. This would happen by means of identifying the antecedent conditions and general laws from the *explanans*, making a clear reference to Hempel & Oppenheim's model

(Figure XV). Such identification would be made using a table of enabling conditions. However, the discovery of a mechanism usually involves several characterizations as data becomes available (CRAVER & DARDEN 2013). Thus, as our case study of pollination services is embedded into a complex system, the activity of identifying each antecedent condition and general law became impractical to the modeler, given the amount of information pertaining to this system, as well as the tricky character of general laws in biology (see MAYR 1982, 1985, 2004; CAPONI 2014). As previously pointed out, the characterization of the phenomenon through the description of every single element that enables it is not feasible in reference to complex phenomena. A strategy for dealing with this complexity would be to develop several characterizations of the phenomenon during the applications of the heuristics. This would also fit the suggestion of Machamer, Darden & Craver (2010) that the intelligibility of the mechanism and the phenomenon is given through the clear exposition of it.

Thus, this heuristics used to identify the *explanans* and *explanandum* throughout the heuristics application and model construction. The *explanandum* is simply the phenomenon to be explained. In our case study, it was first characterized as the "diversity patterns of insect pollinators in agricultural systems". A second characterization strived for narrowing down the phenomenon by selecting a category of pollinator and a specific type of diversity: "functional composition of autochthonous bee communities in agriculture systems". The third construct was related to a specific agricultural system and ecosystem service: "the functional structure of an autochthonous bee community, as well as the maintenance of its pollination services in an agricultural system." It is important to highlight that the creation of this heuristics was inspired in Hempel & Oppenhaim's work on the idea of identify the *explanans* and *explanandum*, but as we assume that it is not always necessary (or possible to have) a full explanation in order to characterize the phenomenon, the idea is to list its properties in ways that do not solve a query or suggest understanding but solely help identify the phenomenon itself. Therefore, what is utmost important in here is the activity and the attempt to identify both *explanans* and *explanandum*.

The *explanans*, in turn, is what explains the *explanandum* (in our case, the series of macro-, meso- and micro-spatial ecological and evolutionary processes). In these characterizations the pollination service in agriculture systems is assumed as an object. In the third construct, the aim is to discuss the mechanisms related to soil use in intense agricultural practices and establish a link between these mechanisms and the functional diversity of bees, appraising response traits and effect traits (see Box I) (*e.g.* Coutinho 2018:*manuscript*).

When this heuristics is interpreted under the light of the contextual theory of scientific understanding, it becomes possible to see a link between it and the way the modeler grasped his phenomenon (Part I, Sect. Preliminary conclusions). Such assumption is framed in terms of the *explanandum* refinement as well as in relation to how the modeler appraised this heuristic:

> I confess that this heuristics was the most subjugated by me, at the beginning of this process, but I realized how much I did not have clarity of the phenomenon in the beginning. This heuristics made it possible to look at my initial research question and reformulate it until I reached the final format that met the expectation of profound contribution in my area of knowledge. It was from this heuristics that I delimited my field of action, avoiding digressions and pointing to the cut in a more objective way. Today I know that thinking about the composition of the functional diversity of bees in tropical agricultural systems is a huge challenge, both from the point of view of specific theoretical questions and from the methodological aspects, and this heuristics helped me in this process of mining and defining my specific scope (COUTINHO, *personal communication*).

All the set of heuristics had in fact a clear feedback toward the phenomenon characterization, and this was perceived by the modeler no matter which heuristics he was applying. Thus, it is possible to say that this heuristics functioned as a conceptual tool with the epistemic role of making the modeler reflect and evaluate his phenomenon, therefore allowing him to grasp his explanation and model.

4.1.2 Mechanism Sketch

It consists of diagrams that aim to establish the relationship between the theoretical frameworks and the phenomenon to be explained, in order to construct a model to explain it. The two most important features of the mechanism sketch are its lack of information and its disposable nature. Any mechanism sketch possesses gaps, gray and black boxes, and may be discarded whenever needed.

Going deeper into the literature on mechanistic models, one realizes that one good way to start elaborating these models can be by creating a "mechanism sketch" and then a "mechanism schema", as discussed by MDC (2000:15). Here we focus on the mechanism sketch, as a prior step to build a mechanism schema (which will be discussed in section 4.1.10). According to these authors, "a *mechanism schema* is a truncated abstract description of a type of a mechanism that can be filled with descriptions of known component parts and activities" (MACHAMER *et al.* 2000:15). In other words, the mechanism schema is a diagram that represents the central features of an idea, in this case, related to a phenomenon and how to explain it.

A mechanism sketch is a much simpler diagram, containing gaps in its stages, missing pieces, black boxes, not filled in by the scientist. It serves to indicate what further works one should do in order to build a mechanism schema. Thus, the mechanism sketch is a kind of draft and will likely be discarded whenever there is a need (MDC 2000:18). Bechtel & Richardson (2010) point out that to discard a draft, in the construction of a mechanistic model, is a good sign because it may indicate and orientate towards the functioning of the system.

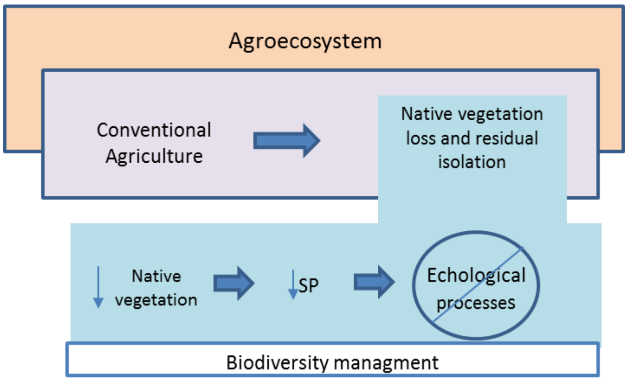
One of the several sources and methods to construct a model is to perceive its parts as placeholders (see HOLYOAK & THAGARD 1995; DUNBAR 1995; SKIPPER 1999). By doing this, it is possible to arrange the steps of the mechanism operation. One way of doing this is to define, hypothetically, the functions of the components in a mechanism, *i.e.*, to ascribe to the entities a number of activities that functionally contribute to the working of the mechanism (see the heuristics 'component operational distinction', Sect. 4.1.5). Another possible way is to identify its modular groups (see the heuristics 'cluster determination', Sect. 4.1.7) (DARDEN 2006). There is no rule or undoubtedly better path to follow. It is possible that in one moment the easier way to go is to identify the activities and then the components. In another moment it may be easier to recognize the activities and then the components. And perhaps in another situation, the modular groups, or nodes, could provide the easier way to unravel the components and activities of the mechanism. Which path to adopt will be decided according to the data available about the phenomenon, the theoretical understanding about the mechanism as well as the scientists decisions.

This heuristics allows the modeler to put pieces together whenever it seems they are related, for instance, the causal relations in the phenomenon. It will thus allow the modeler to rethink the characterization of the phenomenon and the construction of its explanation if needed. Because of its pictorial feature, the mechanism sketch may offer a clearer visualization of the processes involved in the production of the phenomenon, leading to a better understanding. This suggests that the conceptual tool visualizability in the contextual theory of scientific understanding is consistent with the scientific practice in which the understanding emerges.

The strategy to construct a mechanistic model has some similarities to that used to construct conceptual maps, in learning pedagogy (see AUSUBEL *et al.* 1980; NOVAK 1998; NOVAK & GOLWIN 1999). Both are schematic structures that represent a set of concepts immerse in a net of propositions (see TAVARES 2007). This net amounts to a diagram that shows conceptual significance, conceptual significance relation, and conceptual hierarchy (MOREIRA 1998) (*cf*. the heuristics 'hierarchical structure', Sect. 4.1.3). Even though conceptual maps in learning pedagogy are not embedded in the new mechanistic literature, this heuristics suggests that the modeler can start by drawing a sketch of the phenomenon that is closely related to a conceptual map, taking this as a starting point to derive the elements and activities of the mechanistic model. Therefore, conceptual maps can serve, just as the mechanism sketches constructed using them, as instruments to organize and structure the knowledge of the modeler.

Pictorial depictions of mechanistic representations utilize geometrical figures (ellipses, triangles, and circles) to indicate the main concepts, in this case, the components of the mechanisms. Usually, arrows are used in the mechanism diagram to illustrate relations between the boxes or activities (that may or may not be causal). Occasionally there are signs such as "+" and "-" to indicate initiation or activation, and termination or deactivation (LOVE & NATHAN 2015). The following paragraphs present some examples of mechanism sketches created by the philosopher and ecologist to characterize the phenomenon.

Figure XVI: First mechanism sketch in the case study.

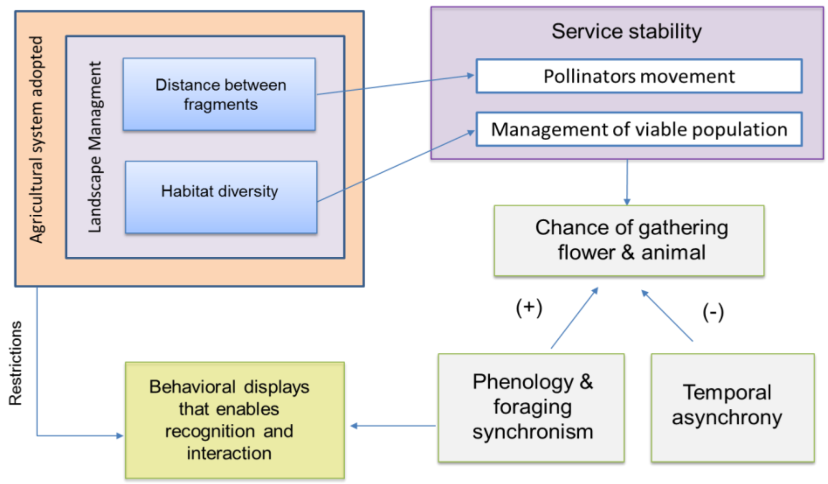


Source: Elaborated by the author.

The first sketch developed in this collaboration of the case study was created by the philosopher and as expected, was rather primitive (Figure XVI). It played, however, an important role in the visualization of our case study as it presented conventional agriculture as an agroecosystem. It is also indicated that conventional agriculture causes loss of native vegetation, which in turn causes the isolation and then the loss of animal and plant species. This will then cause the decrease and even interruption of ecological processes. Biodiversity management has to deal, thus, with the relations among the landscape (including the agricultural landscape), animal, plants, and their functions. This sketch presented several gaps between the elements and therefore was not good enough to generate productive continuity, one of the epistemic tools required for a theory to be intelligible (Sect. 3.2). For instance, what does the arrow linking 'conventional agriculture' to 'native vegetation loss and residual isolation' mean? Generally speaking, what are the events (or processes or phenomena) represented by the arrows in the sketch? The model intends to disclose such relations if there exists any. Assuming that such relations do exist, they may be exposed in the sketch and afterward in the schema.

The second sketch developed in this collaboration was created by the ecologist (Figure XVII) and was not so primitive but was still a little bit simplistic, presenting an agricultural system adopted for a certain kind of landscape management. This management adopts a few features that may influence the phenomenon at stake. Examples include fragment distance and habitat diversity. Fragment distance influences pollinators' movement: the smaller the distance between the fragments the larger is the dispersion of the pollinators in the landscape. As to habitat diversity, the more diverse the habitats, the larger the floral resources. Therewith it can be assumed that there is a viable population of pollinators and, consequently, stability of the ecosystem service they provide. The management of this viable population needs a synchronism between plant flowering and animal presence. For pollen gathering there must be synchronism between phenology and foraging; otherwise, there is no possibility of gathering (temporal asynchrony). If the synchronism is positive, then the encounter between flower and pollinator will happen through behavioral displays and structural features that enable recognition and interactions.

Figure XVII: Second mechanism sketch in the case study.



Source: Coutinho (*personal communication*).

Sometimes, some boxes will not be complete due to unsolved problems (indicating the need for further work), and other times due to the need to use abstraction while building the model (see the heuristics ‘mechanism schema’, Sect. 4.1.10). Black and grey boxes may be filled in gradually[14]. The goal is to produce a sketch/schema where all the parts are glass boxes, that is, in which it is possible to see its content for any instance (DARDEN 2006). The gaps are shown in the black boxes, where neither the components nor the functions are known. In the construction of the model, the intention is to transform the black boxes into gray boxes, where either the components or functions are known. Finally, it is intended that the gray boxes be transformed into glass boxes, where every component and activities shown are known (CRAVER & DARDEN 2013).

The mechanism sketch functions as a draft that can always be discarded or improved. The continuous failure to fill in its parts may lead towards an abandonment of the sketch in favor of another one (DARDEN 2006). For instance, in our case study sketches 1 and 2 were both relinquished. In subsequent sections other sketches are going to be introduced whenever they are best incorporated in the discussion of a heuristics. The important thing to keep in mind is that in our case study the mechanism sketches functioned as an epistemic instrument for the modeler to organize and structure their knowledge about the phenomenon and how to explain it, as clearly stated by the modeler himself:

> One of the most enjoyable and challenging exercises was the application of this heuristics. It was used from the first moment and will be used until my last day of involvement in this research. It was here that I could perceive the universe of variables (ecological drivers) that were relevant to the explanation of my phenomenon and how much there was still no clarity for the *modus operandi* of many of them. In the first proposition of the "mechanism sketch" I realized that I could not arrive at a minimally reasonable scheme of communication of my phenomenon and of the relevant variables for such. At that moment, I realized that communication was a serious problem that I needed to solve, but at that point, I still did not have a theoretical framework enough to make me comfortable to propose something that was convincing and clear to the public that would have access. The heuristics has awakened me to this theoretical gap that existed in me in relation to the phenomenon that I have studied. With each new sketch, new challenges, and solutions, two dimensions of the process of construction of scientific knowledge that led me to lead a process of full immersion in the scientific literature to address the gaps that were gradually perceived. Each new reading enables me to review my sketches (often not materialized, but purely mental), and I will reaffirm my understanding of my phenomenon and the potential contributions that this research can provide [COUTINHO, *personal communication*]

[14] Darden (2006) assumes that the black and gray boxes will be filled in as soon as empirical data is available. For the model built in our case study the source of the empirical data is both direct and indirect. When the data are produced by research projects from the laboratory where the modeler works, we refer to a direct source. When data are obtained from the ecological literature we refer to an indirect source.

Such statement confirms that this heuristics has an epistemic role of visualizability. The capability of the modeler to put pieces together and rethink the characterization of his phenomenon shows that the visualization feature of this heuristics led him to a better understanding of the phenomenon and consequently enhanced the intelligibility of the argument that was being constructed. This also reaffirms the notion of visualization and visualizability as conceptual tools to achieve scientific understanding.

4.1.3 Hierarchical Structure

It aims to identify and locate the amount of levels in which the mechanism (or mechanisms) is organized and nested in the phenomenon superstructure. This heuristics may enable visualize the interaction between different space and time scales.

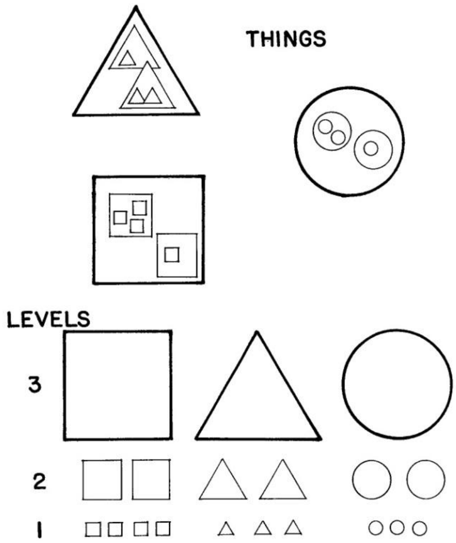
When looking at the mechanistic literature, almost all definitions of 'mechanism' are bound to a certain notion of organization (Sect. 3.2). According to this organization, the elements and activities are disposed in a way that is at least minimally organized. Concerning the hierarchical structure there are a few reflections that must be made, as exposed by Salthe (1985:9):

> It [the basic structure/order of the world] must be a structure that allows causal relationships to exist as well as relationships of control, it must be a structure that will generate complexity (Buchler 1966; Wimsatt 1974; Mandelbrot 1977). It must be a structure that is spontaneously stable (Simon 1969; Soodak and Iberall 1978). It must be a structure that generates things, boundaries (Simon 1969; Mandelbrot 1977; Soodak and Iberall 1978), at least in our interaction with it (Salthe 1983). Very few will do all these; one that will is hierarchical structure – that is, nature viewed as a hierarchy of entities existing at different discrete levels of organization (*e.g.,* Koestler 1967, 1978; Dawkins 1976b; Bunge 1979; Allen ad Starr 1982).

For our case study of pollination services, it was previously assumed by the modeler that the agricultural system is a complex system organized hierarchically, more specifically, in a nested way. In hierarchically structured systems, nature is viewed as a hierarchy of entities existing at different levels of organization (Figure XVIII), such that, as highlighted by Salthe (1985), things exist as wholes with its parts. Each part or whole belongs to a level, or it is the level *per se*. The most interesting aspect is how this drives attention to the idea that "things are ordered by the composition according to scale. Levels are ordered by seriation according to rank. The rank of levels is assigned according to the scale of the things which are their members" (SALTHE 1985:55).

In such a system with several levels, each level may influence one another or not. The components of one level interact with other components at the same level and produce a phenomenon at this level, or at different levels (BECHTEL2015) (Figure XIX). At different levels, their components may use or be beneficiated by the product or phenomena or behavior that occurred at another level, and, therefore, there exists an intersection between different levels. Thus, such hierarchical organization may facilitate the tractability and the characterization of each component of the system (BECHTEL & RICHARDSON [1993] 2010).

Figure XVIII: Things and their correspondence levels.

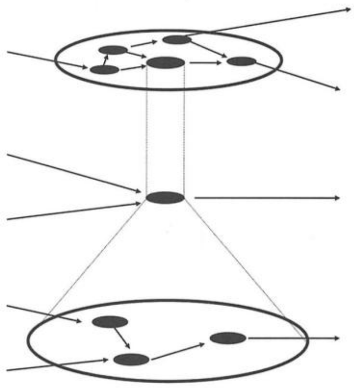


Source: Salthe (1985:56).

Two considerations are highlighted for a better understanding of hierarchical structure of the phenomenon being modeled in our case study. First, levels are *organized*. While spatial structure is important to understand the functioning of the phenomenon, this organization must not be understood as something fixed and stationary, such as, for instance, in the human body where organs and skeleton are organized in a static structure that enables the system's activities (and perhaps vice versa). The spatial localization will not be as important as the activity it allows if and only if its location is not crucial to the action itself. Thus, to realize that levels are organized is to realize that they enable something to happen, while sometimes the components possess rigid spatial locations and sometimes not.

Second, levels are organized and interact consistently within a *timescale*. For example, it is mandatory in our case study of a pollination service to have synchronism between flower and animal – the flower must have pollen available and the pollinator must seek for food for itself and larvae, and for the queen if it is a social species. This example is really interesting because it works with two distinct levels – not hierarchically different (in the sense of bottom-up and top-down) – interacting to produce a sort of byproduct: the pollination itself. It is crucial to notice that the ecological phenomenon also exhibits evolutionary aspects embraced by the *qualitative explananda* that must not be ignored. Therefore, it occurs in distinct timescales, in other words, the timescales of the levels are manifold (MAROM 2010).

Figure XIX: Diagram of levels of mechanism



Source: modified from Craver (2001:66).

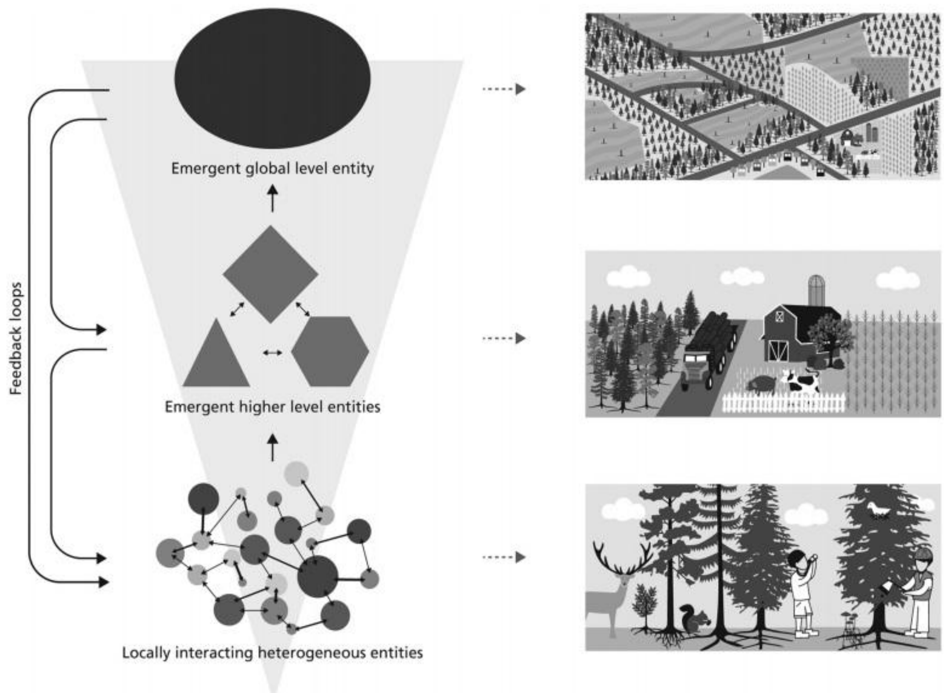
The manifold timescales challenges reductionist interpretations of this heuristics and are coherent with Wimsatt's (1994:x) vision of levels of organization:

> compositional levels [are] hierarchical divisions of stuff (paradigmatically but not necessarily material stuff) organized by part-whole relations, in which wholes at one level function as parts at the next (and at all higher) levels. Though composition relations are transitive (so one could collapse the highest level system to the smallest parts), levels are usually decomposed only one level at a time, and only as needed.

Furthermore, this heuristics is consistent with the second ecological attribute of a complex system (Sect. 2.2), which proposes the idea of a multilevel structure network (FIGURE XX). Note that "community ecology as a field is concerned with explaining the patterns of distribution, abundance, and interaction of species. Such patterns occur at different spatial scales and can vary with the scale of observation, suggesting that different principles might apply at different scales" (LEIBOLD *et al.* 2004:601).

Thus, this heuristics intends to identify the levels in which the mechanisms are organized in the phenomenon superstructure. This will enable visualizations of the interaction between different spatial and temporal scales. As quoted above, this multiplicity is typical in the generation of ecological patterns (see the heuristics 'cluster determinations) (CRAVER 2001).

Figure XX: Conceptual representation of a complex system.



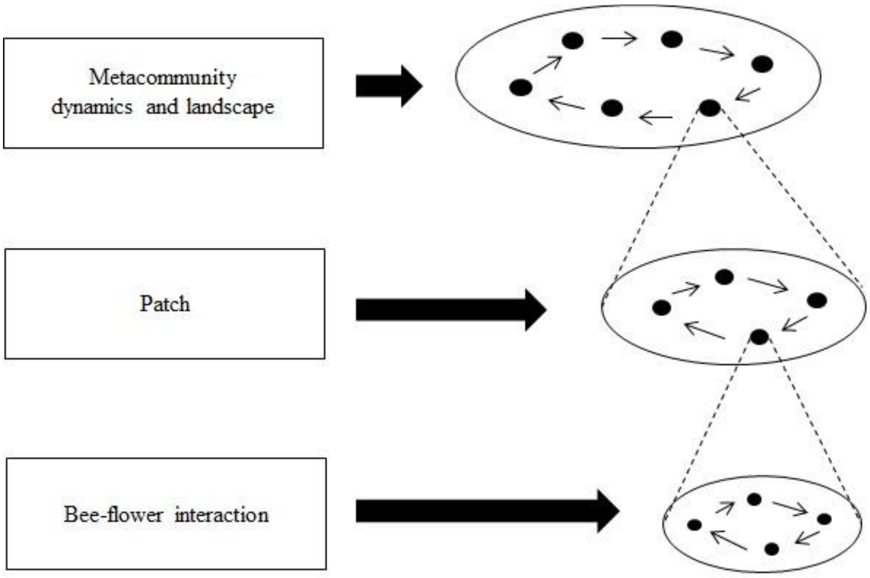
Source: Filotas *et al.* (2014).

The strategy to recognize hierarchical levels and derive a sketch may blend the different approaches of Salthe (1985), Craver (2001) and Filotas *et al.* (2014) showed in previous illustrations. In our case study, this heuristics allowed the modeler to identify three spatial scales in the first phenomenon characterization (Figure XXI). In a top-down view, the larger scale relates the metacommunity dynamics which embrace the landscape theories exposed in section 2.2. One of the elements that enable the higher level to work as a mechanism is the patch. In an agricultural system such as the one concerning the phenomenon, a landscape may possess several heterogeneous patches, from native to secondary vegetation to agricultural field. Each of these patches will possess different dynamics within and a different impact on the pollination system. This uniqueness in the dynamics allows to recognize the lowest level, the bee-flower interaction, as one of the elements of the middle level. Even though this sketch clearly identifies three level of mechanisms, note that neither the elements nor the activities are still established, since this will occur with the assistance of further heuristics, namely 'enabling conditions' and 'operational component distinction'. The illustrations and testimony that follows reasserts the epistemic role these heuristics had for the constant reevaluation of the *explanandum* and *explananda* by the modeler:

> Because my phenomenon was influenced by several drivers operating on these nested hierarchical scales, I realized that I had a bigger challenge: what are the most important drivers within each scale and which are the most relevant scales to include in the model? Heuristics led me to a deeper analytical state of search within each level of the hierarchy. With the use of this heuristics, I could perceive numerous tradeoffs and synergisms between hierarchical levels that would be crucial in explaining the phenomenon, which was also possible thanks to the use of the next two heuristics [COUTINHO, *personal communication]*.

Another example of the use of this heuristics in the case study is illustrated in Figure XXII. In this illustration the mechanism sketch is more elaborated and the phenomenon is now identified by the modeler with four levels: large, meso, small and smallest scale.

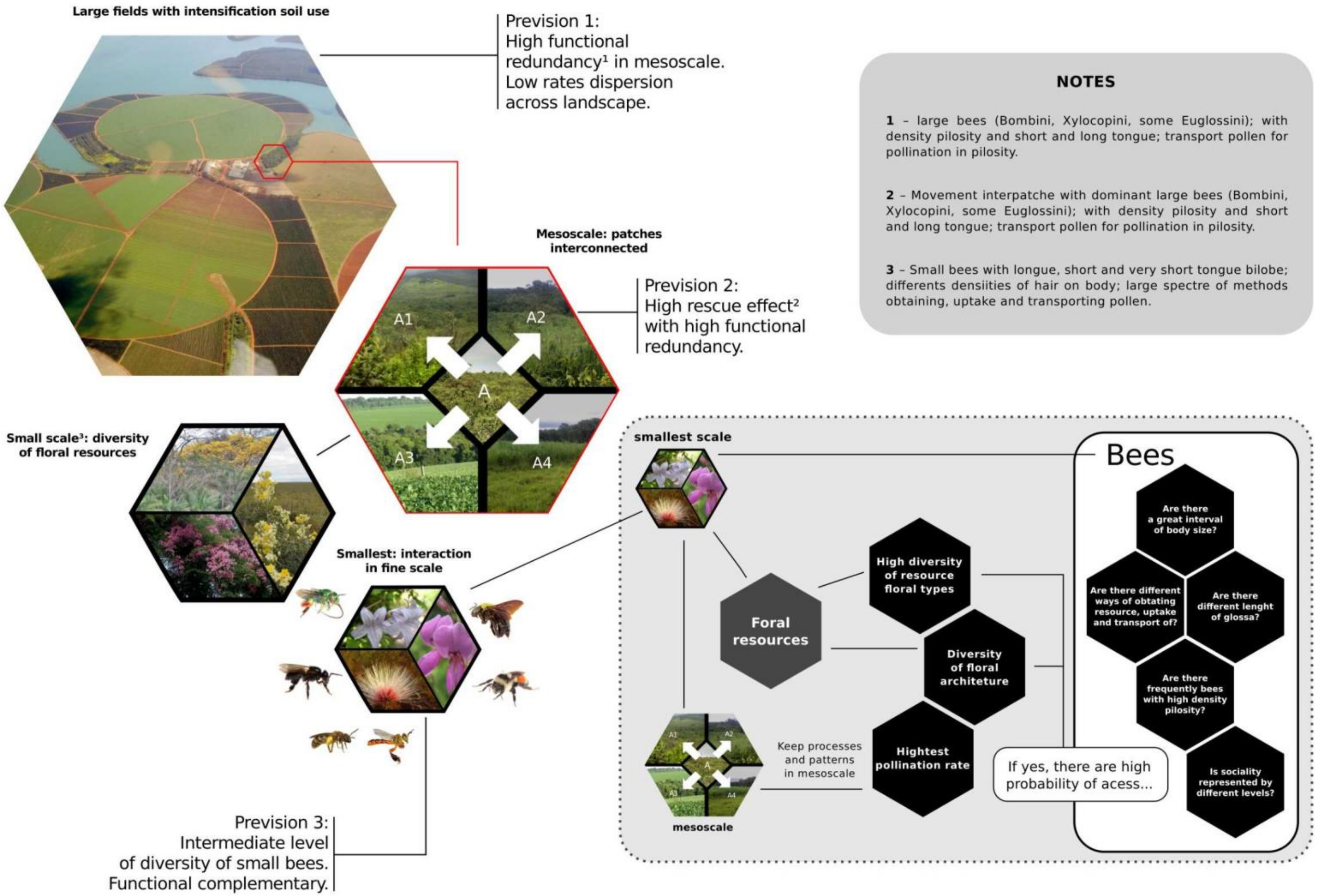
Figure XXI: Sketch showing three spatial scales recognized by the modeler in the phenomenon.



Source: Coutinho (*personal communication*).

Even though the components and activities at each level are not made explicit, the modeler can still recognize some expected behavior for each level which he attributes to some bee's features. For instance, at the smallest level the diversity of small bees works as a functional complement to the diversity of larger bees moving between the patches interconnected at the mesoscale. Although the information is not clearly connected by the modeler, it is possible to see the components (say, bees), the activities (say, pollination), the spatial organization (say, flower) and, the external regulatory agents (say, distance between patches).

Figure XXII: Third mechanism sketch (for more information, *vide* text).



Source: Coutinho (*personal communication*).

Thus, this heuristics shows that the spatial localization, which is a crucial factor for mechanisms (Sect. 3.2), is not only identified and reconstructed for biochemical, neurobiological and physical processes, but also for ecological phenomena involving interactors and levels spanning over a wider range of scales

4.1.4 Enabling Conditions

It is the selection of the most relevant variables of the mechanisms that originate the phenomenon. This can be done via set-up condition or via the information of each theoretical pillar gathered into groups of variables.

The heuristics enabling conditions concerns the selection of the most relevant variables of the mechanism that produces the phenomena. The information of each theoretical pillar, that might present an explicit relation between the components, or present an explicit activity, is gathered in a group of variables that enables the construction of the model.

The variable set that will be part of the model was chosen according to three theoretical pillars because they underly the understanding of the relationship network involved in the ecological process. They are metacommunity theory and its interface with landscape ecology; conventional agricultural model; and the natural history of interactors (Table D).

This heuristics was created based on MDC (2000) and Salthe (1985). According to Salthe (1985), natural entities and processes exhibit various patterns that may be related to each other. These patterns and their relations may reveal information about the world that is not directly observed – they reveal evidence about their possible structure. It is important to consider that not every pattern reveals information. Thus, how is it possible for someone to differentiate patterns that reveal information from patterns that do not? The suggestion for this inquiry arose from the reading of MDC's (2000) work. They assert that the beginning of a mechanism description starts with the identification of the start or set-up conditions. These conditions may be structural properties, spatial localization, and entities that will be crucial to carry out the activities at the first moment in the operation of the mechanism – the set-up conditions.

The following example illustrates how this heuristics was identified in our case study. In the ecological framework, it is acknowledged that the high density of bees' bristles is a proxy to the efficiency in transferring a large amount of pollen grains in a given agricultural system (effect trait). This may be a condition that increases the chance of high pollen flow in a given landscape among different plant species of a given agroecosystem. This will contribute significantly to the reproduction of many of these plant species. This process, in turn, maintains a high diversity of resources in the landscape that maintains bee populations in this system, including bees with high bristle density in the body, since the more plants can reproduce, the more the supply of floral resources in time and space. The agroecosystem, however, requires other ecosystem processes at the landscape scale: pest control, nutrient cycling, water supply, among others (COUTINHO 2018:*manuscript*).

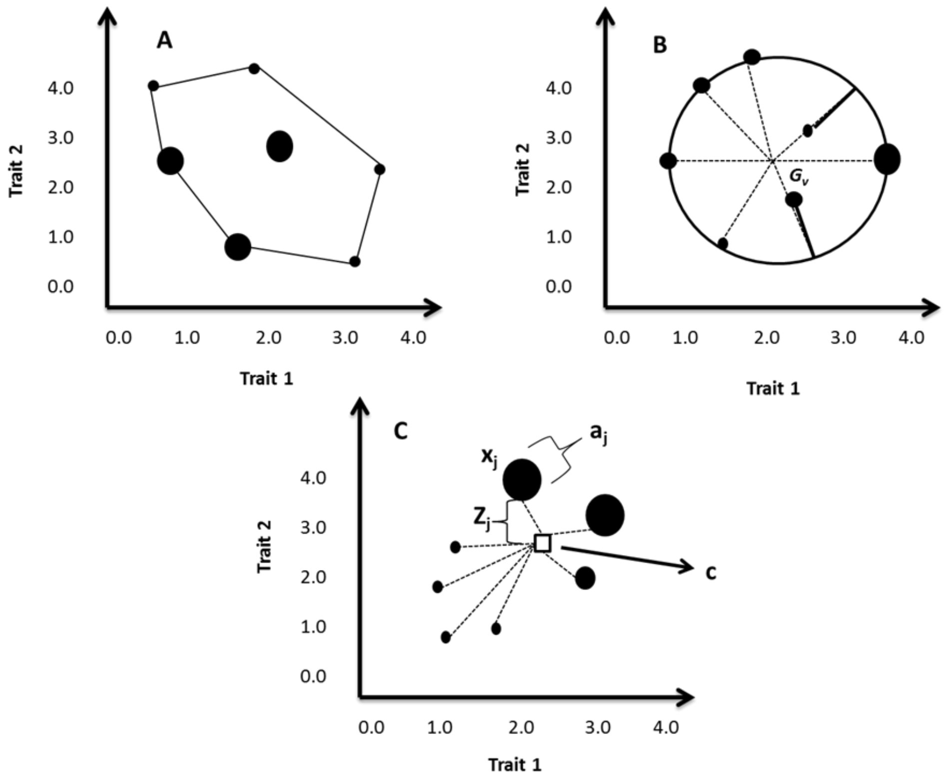
Table D: Enabling conditions set used to help develop the phenomenon sketches. Variables are selected according to each theoretical pillar.

Theoretical Pillar	Attributes of the system	
Metacommunity theory and interface with landscape ecology	Fragment distance	
	Fragment size	
	Resources availability	
	Structural connectivity	
	Patches arrangement	
	Patches shape	
	Habitat diversity	
Conventional agricultural model	Soil mechanization	
	Cropland shape	
	Distance to natural areas from cropland and others natural areas	
	Agrochemical use	
	Suppression of native vegetation	
Natural history of interactors	Native Bees	Locomotion capacity
		Body size
		Nest behavior
		Dietary specialization
	Visited flowers	Stigmatic receptivity
		Pollen availability and other resources
		Flower geometry
		Flowering time

Source: Coutinho (*personal communication* [modified by Poliseli]).

The goal of this heuristics is to identify the most relevant variables of the phenomenon, but one interesting aspect to notice is that at the beginning of this enterprise this heuristics was achieved by means of the explicit development of content tables. However, the more elaborated the sketch became, the more information was aggregated, and vice versa. This allowed a refinement of the phenomenon characterization, and, therefore, of the *explanans* and *explanandum*. In this sense, this heuristics changed from a simple construction of tables to information gathered through ecological graphs and mathematical indices (Figure XXIII). Although mathematical indices do not point to an explicit causal relation, they are good indicators of such relations and are widely used for management in ecological studies. This also shows the epistemic role that such graphs and indices play in the achievement of understanding of the *explanandum* and *explanada*, when they function as conceptual tools (Sect. 1.2.2).

Figure XXIII: Three different indices that reflect distinct properties of functional diversity. **A:** functional richness expressed by the volume occupied by the species present in the community in a multidimensional space of traits. **B**: functional divergence expressed by the distance of the species in relation to the gravity center of the functional space (Gv). **C:** functional dispersion expressed by the medium distance of individual species to the centroid of all species (Xj): position of species j; (Zj): distance from species j to centroid c; aj: species abundance; c: centroid of the species present in the community. The size of the circles represents the distinct abundances of species in the community.



Source: modified and extracted from Coutinho (2018).

It is important to realize that even though the enabling conditions are those variables that possess information about the phenomenon structure, this structure is not exclusively provided by these variables. There will exist some features that are delimited by some constraints or boundaries of the systems. They will be discussed in a later section, on the heuristics ‘external regulatory agents’.

4.1.5 Operational Component Distinction

Its goal is to distinguish the components and functions of the enabling conditions within the mechanism and specify the relations and boundaries between those components. If this information is not available yet, it is highly recommended to use the procedures of decomposition & localization, forward & backward chaining, and synthetic & analytic strategies to achieve this goal.

The operational component distinction is, perhaps, the only heuristics that should be necessarily performed subsequent to another heuristics - the ‘enabling conditions’. Here, the researcher will identify the components and functions of the enabling conditions within the mechanism and specify the relations and the boundaries (assuming that they exist) between those components, establishing a causal relation.

The key for developing a mechanistic explanation is to determine the components of a system and their functions (BECHTEL & RICHARDSON [1993]2010). To support previous assumptions on components and/or functions the modeler may apply the strategy of decomposition and localization (BECHTEL & RICHARDSON [1993]2010) combined with the strategy of forwarding and backward chaining (DARDEN 2002, 2006). The decomposition approach assumes “that one activity of a whole system is the product of a set of subordinate functions performed in the system” (BECHTEL & RICHARDSON [1993]2010:23). Thus, it is possible to isolate physically the components of the system and determine their functions because even a small number of such activities will be minimally interactive. The localization approach, in turn, leads to the identification of the activities, or capacities, realized by the parts previously decomposed. Some actions will be easily identified whereas in the case of others it will be necessary to appeal to functional tools. This process may be facilitated by the synthetic and analytic strategies with excitatory and/or inhibitory stimuli (*cf.* Sect. 3.2).

In spite of the recommendation to use the sequence of decomposition/localization and forward/backward chaining, some parts will usually be easily identified without any of those efforts. Other times, those instruments will be necessary. Nevertheless, there will be moments where only a component or a function will be identified, but not both. Sometimes the activity may be identified without the recognition of the components. And other moments the component may be identified without discovering the exact activity it realizes. When there are such uncertainties, we will refer to an “operational component”.

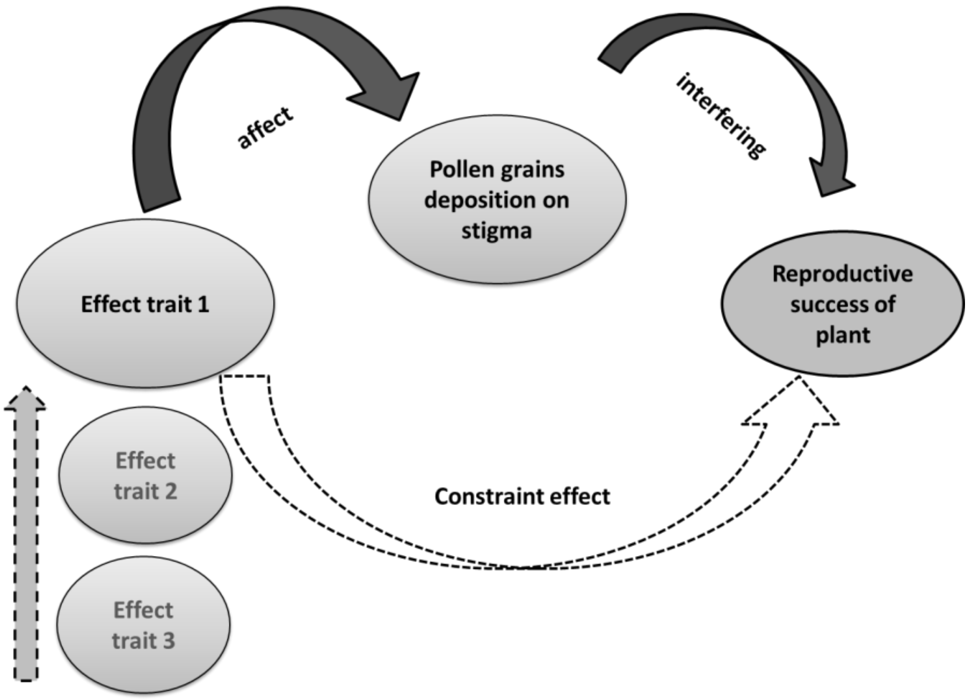
Table E: Set of operational component distinctions of the enabling conditions.

<table>
<tr><th colspan="3">Metacommunity theory and its interface with landscape ecology</th></tr>
<tr><th colspan="2">Attributes of the system</th><th>Dynamics/What promotes</th></tr>
<tr><td colspan="2">Fragment distance</td><td>Bees movement</td></tr>
<tr><td colspan="2">Fragment size</td><td>Colonization</td></tr>
<tr><td colspan="2">Structural connectivity</td><td>Pollen flow</td></tr>
<tr><td colspan="2">Patches arrangement</td><td>Isolation of populations</td></tr>
<tr><td colspan="2">Habitat amount</td><td>Probability to sustain viable populations</td></tr>
<tr><td colspan="2">Habitat diversity</td><td>Resources availability diversity</td></tr>
<tr><th colspan="3">Conventional agricultural model</th></tr>
<tr><th colspan="2">Attribute</th><th>Dynamics/What promotes</th></tr>
<tr><td colspan="2">Soil mechanization</td><td>Soil compaction</td></tr>
<tr><td colspan="2">Cropland shape</td><td>Bees movement</td></tr>
<tr><td colspan="2">Distance to natural areas from cropland and others natural areas</td><td>Bees movement / polinic flow / connectivity of populations</td></tr>
<tr><td colspan="2">Agrochemicals use</td><td>Bees health and survival</td></tr>
<tr><td colspan="2">Suppression of native vegetation</td><td>Less habitat amount</td></tr>
<tr><td colspan="2">Crop rotation</td><td>Temporal dynamics in resource availability</td></tr>
<tr><th colspan="3">Natural history of interactors</th></tr>
<tr><th>Domain</th><th>Attribute</th><th>Dynamics/What promotes</th></tr>
<tr><td rowspan="4">Native Bees</td><td>Locomotion capacity</td><td>Long-distance transposition</td></tr>
<tr><td>Body size</td><td>Long-distance transposition</td></tr>
<tr><td>Nest behavior</td><td>Abundant or scarce substrate</td></tr>
<tr><td>Dietary specialization</td><td>Restricted or broad diet</td></tr>
<tr><td rowspan="4">Visited flowers</td><td>Stigmatic receptivity</td><td>Compatibility with foraging behavior</td></tr>
<tr><td>Pollen availability and other resources</td><td>Floral attractiveness and reward content</td></tr>
<tr><td>Flower geometry</td><td>Access to a narrower or broader set of bees</td></tr>
<tr><td>Flowering time</td><td>Time range for the supply of the resources</td></tr>
</table>

Source: Coutinho (*personal communication* [modified by Poliseli]).

Table E applies these considerations to the case study of pollination by presenting a set of operational components developed by the modeler according to the three theoretical pillars he judged relevant for the phenomenon. The information on the operational components was extracted from published ecological works. It didn't become sufficiently clear how the modeler used the strategies of localization/decomposition and backward/forward chaining to achieve the goal of such heuristics. Perhaps, this suggests that these strategies proposed by Darden (2002, 2006) and Bechtel & Richardson ([1993]2010) are not so demanding when one is attempting to identify components and activities, and consequently construct mechanistic models, so that the modeler was able to elaborate it through mental operations, where we only had access to their products. Reinforcing this idea, a strategy was elaborated by the modeler indicating the steps needed to recognize the effect traits, response traits and properties of functional diversity more relevant to the phenomenon (Figure XXIV).

Figure XXIV: diagram indicating steps for the recognition of relevant effect traits related to the pollination in a system. Such diagram was built according the functional organization approach (Nunes-Neto et al., 2014).



Source: Coutinho (2018*: manuscript*).

According to Figure XXIV an effect trait (1, 2, 3) will be relevant if, and only if, its exclusion implicates changes in the deposition of grains of pollen on the stigma. This will consequently reduce the amount of fruits and/or seeds of the target plant species, which will deviate from the maximum potential of the species. This constraining effect of the effect trait on the reproductive success of the plant should guide the selection of relevant traits in the analysis. An example of how this diagram worked in the case study will follow.

An important aspect of the effect traits considering the reproductive success of a species is that pollination sometimes may be considered as efficient from the pollinator's perspective but processes such as inadequate distribution of resources can lead to a reduction in the formation of fruits and seeds (COBERT 1998; CANE & SCHIFFHAUER 2003). This clarifies why one should not attribute to the effects traits only one exclusive role in the reproductive success of plant species, being necessary to evaluate a diversity of factors that may influence reproductive success. Thus, if the goal is for example to establish the diversity of effect traits with the pollination service, the following question is posed: how much does an effect trait contribute to the fertilization of eggs in the investigated plant? In this moment, the modeler will make a more judicious choice of the core attributes that fit the concept of function adopted in this framework. This will call attention to empirical studies already in literature that clarifies the role of the effect traits and rank them according to a hierarchy of importance (COUTINHO 2018:*manuscript*).

One interesting aspect that also changed with the process of *explanans* and *explanandum* refinement was the use of mathematical indices, as addressed in the previous heuristics. In the heuristics 'enabling conditions' the response traits were approached individually, but with the use of these indices, the set of traits came to be approached from a multidimensional perspective. The most used index was functional dispersion. This metric quantifies the medium distance of each species of the community toward the centroid of a multivariate space previously defined (LALIBERTE & LEGENDRE 2010). In the case study, this index represents a feature of the community. For instance, the extent to which species occupy a volume formed by a set of functional traits indicates how much functional complementarity occurs in a given community and, also, the complementarity consequences for the pollination service. Despite the fact that this multivariate perspective is not often used to analyze bee communities, this approach may be interesting to compare communities over a spatial gradient. This may also be an initial step to discuss the features that are part of the structuring processes of these communities (COUTINHO 2018:*manuscript*).

As this heuristics is concerned with identifying and distinguishing the components and functions of the enabling conditions, it can be conceptualized as a conceptual tool of causal reasoning based on the contextual theory of scientific understanding (Sect. 1.2.2). This is in accordance with the idea that causal reasoning not only discloses the underlying structure of causal relations but also because improve the abilities of the scientist that are clearly reflected in the strategy elaborated by the modeler to recognize relevant effect traits in the phenomenon (Figure XXIV), being also consonant with his testimony as follows:

> […] At the outset of this process, distinguishing the key aspects in the interactions between variables and potential changes brought about by these interactions was not an easy task. This heuristics trained my analytical ability in the universe of variables I was exposed to, allowing me to see the emergence of the phenomenon as crucial point, eliminating excesses that could even hinder the understanding of the most central processes. In constructing the model, this heuristics made it possible to have more clarity about the sequence of events within a more complex chain of interactions and how they related to each other, provoking significant changes in the system of interest that we have investigated (functional diversity). I can say that my power of synthesis in the face of the complexity exposed was one of the great gains that this heuristics enabled me [COUTINHO, *personal communication*].

4.1.6 Evidence Frequency

It intends to indicate causality between the elements of the enabling condition table according to probabilistic and mechanistic information already available in the scientific literature or gathered through previous heuristics

This heuristics was formulated mainly based on the literature on medicine that concerns diagnoses and treatments. Even though this heuristics at first sight might look as having no relation with mechanistic explanation, evidence-based medicine, more specifically the mechanism-based reasoning, relies on the identifications of mechanisms, as will be further exposed below. Given that this heuristics concerns mechanism-based reasoning, it is justified to include it in our heuristics set.

In order to make decisions about patient care, for instance what treatment intervention to indicate, a previous diagnosis is necessary (CLARKE *et al.* 2014). How to link the symptoms to their causes has been a prolific theme in health care. One practice with such purpose is the evidence-based medicine (EBM). The philosophical origins of EBM goes back to mid-19th century Paris and even earlier, and EBM is still a hot topic for clinicians, public health practitioners, public health planners, and the public (SACKET *et al.* 1996).

By evidence-based medicine one means the conscientious, explicit, and judicious use of the current best evidence for decision-making about patient care (SACKET et al. 1996:71). EBM uses a bottom-up approach to categorize the evidence for a causal claim by means of evidence of correlation. The procedure for grading the evidence of correlation, therefore, produces and *evidence hierarchy*. The evidence hierarchy ranks evidence by establishing the causal claims it supports (CLARKE *et al.* 2014). There is a theoretical framework for the formulation of an evidence hierarchy[15] proposed by the Canadian Task Force (1979) (see Table F).

The nature of evidence may vary from individual clinical expertise to external evidence from systematic research (SACKET *et al.* 1996), *e.g.*, statistical trials and mechanism-based reasoning – also called probabilistic evidence and mechanistic evidence (RUSSO & WILLIAMSOM 2007, 2011). Statistical trials may be randomized controlled trials (RCTs), cohort studies, case-control studies, case series and *n* of 1 trials, while mechanism-based reasoning may be based on evidence obtained by laboratory experiments, literature reviews, individual patient case studies, textbook consensus and expert testimony (CLARKE *et al.* 2013, 2014).

Table F: Levels and quality of evidence.

Level of evidence	Quality of evidence
I	Evidence obtained from at least one properly randomized controlled trial.
II-1	Evidence obtained from well-designed cohort or case-control analytic studies, preferably from more than one center of the research group.
II-2	Evidence obtained from comparisons between times or places with or without intervention. Dramatic results in uncontrolled experiments (such as the results of the introduction of penicillin in the 1940s) could also be regarded as this type of evidence.
III	Opinions of respected authorities, based on clinical experience, descriptive studies or reports of expert committees.

Source: Canadian Task Force (1979:1195).

In spite of the positive results for mechanisms in biochemistry (Sect. 3.2), usually evidence-based medicine holds that mechanism-based reasoning is a second-rate evidence in comparison to evidence of correlation, as made explicit by the Oxford Centre for Evidence-Based Medicine (OCEBM 2011) (Table G). Note that mechanism evidence is restricted to the lowest levels of the hierarchy, namely level five. In turn, the higher levels, which are the most reliable ones, concern evidence from statistical trials (CLARKE *et al.* 2013, 2014).

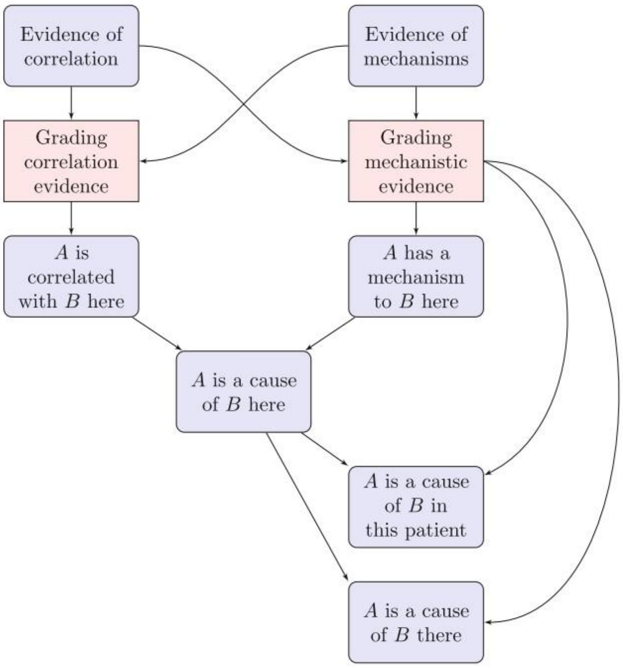
Despite this prevailing scenario, both kinds of evidence possess limitations. Probabilistic evidence is fallible, as evidence provided by any kind of statistical study, and must deal with the problem of confounding variables, while mechanism evidence must handle the masking problem (CLARKE *et al.* 2014). Thus, to mitigate these frailties the Russo-Williamson Thesis (RWT) defends that both mechanism evidence and probabilistic evidence

[15] In the philosophical literature, evidence hierarchy and randomized controlled trial (RCT) are considerably controversial subjects. For discussions on the topic, see Papineau (1994), La Caze *et al.* (2008, 2009), Cartwright (2010), Cartwright & Munro (2010), Stegenga (2011), Northcott (2012), Worrall (2002, 2007, 2010).

are required to establish causal claims. They assert: "[t]o establish causal claims, scientists need the mutual support of mechanisms and dependencies. […] The idea is that probabilistic evidence needs to be accounted for by an underlying mechanism before the causal claim can be established" (RUSSO & WILLIAMSON 2007:159).

According to RWT, to establish a causal claim is necessary to establish a mechanistic claim as well as a correlation claim (Figure XXV). Therefore, it is mandatory to describe and grade those kinds of evidence. Once they are displayed, they will serve each other as complementary tools. For instance, the evidence of mechanism will evaluate whether statistical studies have been appropriately interpreted, while the evidence of correlation will determine the net effect of a mechanism and whether there exists other mechanisms concealed (CLARKE *et al.* 2014). This account plays a major role in this heuristics in our study case, because it takes into account the complementarity of distinct kinds of evidence.

Figure XXV: The diagram illustrate evidence of mechanism treated equally in cooperation with evidence of correlation. To establish a causal claim is necessary to establish a mechanistic claim, a correlation claim and grade them. The evidence of mechanism needs to inform whether statistical trials and were properly applied while the evidence of correlation needs to inform the net effect of a mechanism.



Source: Clarke *et al.* (2014:355).

An interesting aspect of RWT is that it proposes a switch at the causal accounts. There are two standards interpretations of causality in the biomedical sciences - the *difference-making account* and the *mechanistic account* (RUSSO & WILLIAMSON 2011). The approach suggested by RWT is, in turn, that biomedical sciences should utilize an *epistemic theory of causality*.

The *difference-making theories* suggest that the cause make a difference or have an effect on the occurrence of an event. This theory may be of three kinds: manipulative/interventionist; counterfactual; and probabilistic. For EBM this causal claim is usually represented by the probabilistic and statistical evidence, in the evidence hierarchy. The *mechanistic theory*, in turn, asserts that C is a cause of E if there exists a mechanism linking C to E (WILLIAMSON 2011). This approach can be of two kinds: process theories and complex-systems mechanisms theories.

The *epistemic theory of causality* proposed by RWT suggests that evidence in biomedical sciences, besides the mechanism and statistical sources, is also indicated by inference (RUSSO & WILLIAMSON 2007, 2011). Thus, in this context:

> epistemic account of causality interprets causal claims as directly charting successful inferences (predictions and explanations). Thus our web of causal claims is used to draw the sorts of inferences alluded […] and can be thought of as a map of the inferences that it licenses. In short, such an account treats a body of causal claims as an inferential map (Russo & Williamson 2011:567).
> According to epistemic theory, causal claims need to be made on the basis of evidence of both difference-making (statistical associations, randomized controlled trials etc.) and mechanisms (Russo and Williamson 2007; 2011), as well as evidence such as temporal information and information about the nature of the events in question (Russo & Williamson 2011:568).

Considering the arguments above, the expectation is that this heuristics can at a first moment frame a chart that indicates causality between the elements of the enabling conditions. This chart would be similar to the evidence hierarchy in biomedical sciences (Table F and G). Likewise, evidence would result from probabilistic and mechanistic data already available in the ecological literature. Presumably, this chart – showing evidence hierarchy – should be equivalent or similar to the enabling conditions set. The difference is the addition of a weight (Table H) to the evidence, according to its frequency in the explanation of certain relations. Thus, this weight informs the frequency in which a relation between ecological processes appears in the literature. Such recurrence might suggest that a causal relation exists between those ecological processes. This might facilitate the identification of the components in the mechanism and their activities, being a helpful tool for the heuristics 'operational component distinction'. If the enabling conditions set and the evidence hierarchy chart should be considered the same or not is a choice made by the modeler.

Table G: levels of evidence.

Oxford Centre for Evidence-Based Medicine 2011 Levels of Evidence

Question	Step 1 (Level 1*)	Step 2 (Level 2*)	Step 3 (Level 3*)	Step 4 (Level 4*)	Step 5 (Level 5)
How common is the problem?	Local and current random sample surveys (or censuses)	Systematic review of surveys that allow matching to local circumstances**	Local non-random sample**	Case-series**	n/a
Is this diagnostic or monitoring test accurate? (Diagnosis)	Systematic review of cross sectional studies with consistently applied reference standard and blinding	Individual cross sectional studies with consistently applied reference standard and blinding	Non-consecutive studies, or studies without consistently applied reference standards**	Case-control studies, or "poor or non-independent reference standard**	Mechanism-based reasoning
What will happen if we do not add a therapy? (Prognosis)	Systematic review of inception cohort studies	Inception cohort studies	Cohort study or control arm of randomized trial*	Case-series or case-control studies, or poor quality prognostic cohort study**	n/a
Does this intervention help? (Treatment Benefits)	Systematic review of randomized trials or *n*-of-1 trials	Randomized trial or observational study with dramatic effect	Non-randomized controlled cohort/follow-up study**	Case-series, case-control studies, or historically controlled studies**	Mechanism-based reasoning
What are the COMMON harms? (Treatment Harms)	Systematic review of randomized trials, systematic review of nested case-control studies, *n*-of-1 trial with the patient you are raising the question about, or observational study with dramatic effect	Individual randomized trial or (exceptionally) observational study with dramatic effect	Non-randomized controlled cohort/follow-up study (post-marketing surveillance) provided there are sufficient numbers to rule out a common harm. (For long-term harms the duration of follow-up must be sufficient.)**	Case-series, case-control, or historically controlled studies**	Mechanism-based reasoning
What are the RARE harms? (Treatment Harms)	Systematic review of randomized trials or *n*-of-1 trial	Randomized trial or (exceptionally) observational study with dramatic effect			
Is this (early detection) test worthwhile? (Screening)	Systematic review of randomized trials	Randomized trial	Non -randomized controlled cohort/follow-up study**	Case-series, case-control, or historically controlled studies**	Mechanism-based reasoning

*** Level may be graded down on the basis of study quality, imprecision, indirectness (study PICO does not match questions PICO), because of inconsistency between studies, or because the absolute effect size is very small; Level may be graded up if there is a large or very large effect size.**

**** As always, a systematic review is generally better than an individual study.**

Source: Oxford Centre for Evidence-Based Medicine (2011).

Table H: this table indicates how causal relation and its frequency should be represented. The variables suggests the events with a causal relation and the recurrence indicates its frequency in the literature. Arrow width is a representation of its frequency in literature.

Variable	Recurrence
X	30
Y	12

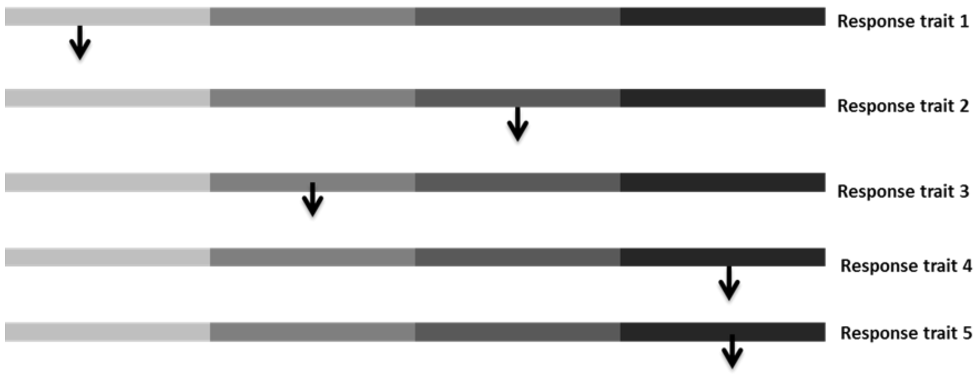
Source: Coutinho (personal communication).

Table H is a pictorial representation of the expectations concerning this heuristics at first, even though we do not have any clear evidence that such a chart was constructed by the modeler. Considering that the application of the heuristics changed along with the delimitation of the *explanans* and *explanandum* by the modeler (see the modeler's testimony below), it is possible to assume that this information was gathered by the modeler through graphs such as that shown in Figure XXV. Independently of the way the modeler chose to represent this heuristics, it clearly shows how causal reasoning may function as a conceptual tool that helped him elaborate his explanation, making model more intelligible and understanding achievement more likely. This is suggested by the modeler's commentaries themselves:

> This heuristics made possible some very important aspects in the process of constructing the model: to quantify how much evidence I had regarding the explanatory power of metacommunity models in relation to the phenomenon of interest; State of the art of how they were treating the bee's functional diversity (theoretical and methodological contributions) and identification of potential gaps that could be filled in. I initially neglected the role of this heuristics because I did not know the potential that it would have in the construction of our product. When I refined my object of study (via the heuristics 'phenomenon characterization'), I realized that this heuristics here would enable me to provide a more accurate diagnosis of how much was understood about the phenomenon of interest, as well as to identify the possible sources of conflict in the literature, starting with the next step that was to look for possible explanations for such conflicts (when they existed, like the one I mentioned above). This heuristics is present not only in this stage of my thesis but also permeates other chapters. It allows a kind of x-ray of how much we actually understand about something or think we understand, being a crucial tool in the critical analysis of the empirical literature on the subject [COUTINHO, *personal communication*].

In Figure XXVI the weight of the evidence is represented by the degree of sensitivity of the response traits. The bars represent five hypothetical response traits and the colors indicates the degree of sensibility concerning an ecological driver (light gray is the most sensitive and black is the most resistant in relation to the driver). The downward arrows indicate the response of this hypothetical species to each trait in this representation. To have a better picture of how this heuristics worked in the study case, suppose, for instance, that response traits 1, 2, 3, 4, and 5 are body size, gloss size, nesting habits, sociality, and vital cycle, respectively. If the response trait 1 is the bee`s body size then the different gray shades would correspond to distinct size classes. When environmental drivers such as suppression of natural vegetation and fragmentation of landscape are added to this scenario, it will be possible to see how they will influence bee mobility and dispersion between the patches (KREWENKA *et al.* 2011; ARANDA & GRACIOLLI 2015). In this context, the hypothetical bee would possess a small size. The body size is a highly important feature regarding the mobility between patches in a fragmented landscape (GREENLEAF *et al.* 2007; WARZECHA *et al.* 2016). Bees with large body size possess a larger mobility, which is important considering the occupation of wide areas that suffered reduction of native vegetation and are composed, therefore, by relatively isolated patches (WARZECHA *et al.* 2016). The expectation is that the probability of reduction of this population would be lower than the other one in the opposite extreme (*i.e.* bees with small body size).

Figure XXVI: Graph used to classify species according to their response traits from the perspective of an analysis of the degree of sensitivity of the multiple states of each trait (for further explanation, *vide* text).



Source: Coutinho (2018:manuscript).

If you consider the other response traits in the graph, which influence the same species, we can conclude one needs to evaluate each of these features with regard to the probability of the occurrence of this bee in the landscape. For instance, the fact that they are social animals with a multi-vital cycle reduces the negative effect of their small body size, because they possess a larger amount of individuals in the hive with frequent reproductive events throughout the year (DE PALMA *et al.* 2015). This might increase its capacity of abidance in the landscape despite its small mobility. Therefore, some response traits constrain the effects of other response traits, depending on how much they are able to guarantee the maintenance of individuals of a given species in a given scenario (COUTINHO 2018:*manuscript*).

4.1.7 Cluster Determination

It aims to furnish a solid ground and to grant robustness to the operational component distinction, to the enabling conditions and to the hierarchical structure.

This heuristics may be applied for two distinct purposes: (i) furnishing a solid ground to the operational component distinction (see the heuristics 'operational component distinction') by providing elements to attribute weights to the evidence frequency table (see the heuristics 'evidence frequency'); and (ii) granting robustness to the enabling conditions (see the heuristics 'enabling condition') as well as to the hierarchical structure (see the heuristics 'hierarchical structure'). It is possible to fulfill these purposes with the utilization of net typology[16].

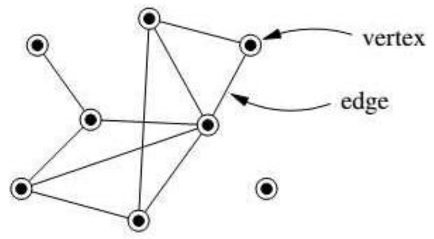
"Networks are everywhere" (BARABÁSI & BONABEAU 2003:62). It is possible to apply nets for the representation of electric circuits, roadways, organic molecules, ecosystems, sociological relationships, databases, and so on (GROSS & YELLEN 2003). Networks are constituted of several nodes (or vertices), and each node is connected to each other by a link (edge) (NEWMAN 2003:168) (Figure XXVII). This is the basic structure of a network, but there exist several ways through which a graph can get more and more complex (Figure XXVIII).

> A set of vertices joined by edges is only the simplest type of network; there are many ways in which networks may be more complex than this [...]. For instance, there may be more than one different type of vertex in a network, or more than one different type of edge. And vertices or edges may have a variety of properties, numerical or otherwise, associated with them. Taking the example of a social network of people, the vertices may represent men or women, people of different nationalities, locations, ages, incomes, or many other things. Edges may represent friendship, but they could also represent

[16] Networks are also called graphs in mathematical language. Graph theory is a part of discrete mathematics that studies the elements and the relations of a set. Euler's solution to the Königsberg bridge problem is considered as the first true proof of networks (NEWMAN 2003:169) (for more information on graphs, see BIGGS *et al.* 1986; AHUJA *et al.* 1993; HARARY 1995; BOLLOBÁS 2001; WATTS 2003).

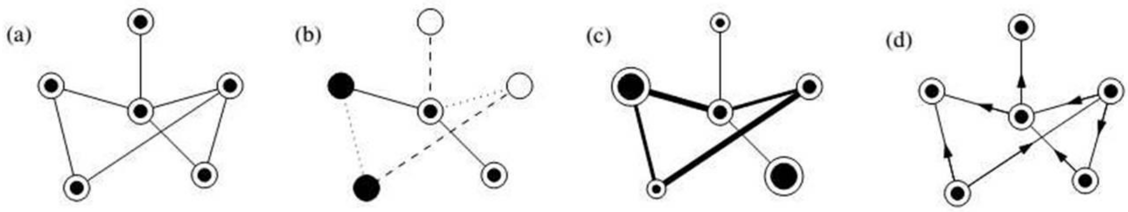
> animosity, or professional acquaintance, or geographical proximity. They can carry weights, representing, say, how well two people know each other. They can also be directed, pointing in only one direction. […] Directed graphs can be either cyclic, meaning they contain loosed loops of edges, or acyclic, meaning they do not (NEWMAN 2003:171/2).

Figure XXVII: A small network with eight nodes or vertices and ten edges



Source: Newman (2003:169).

Figure XXVIII: Different types of networks: (a) simple network; (b) network with discrete vertex and edge types; (c) network with varying vertex and edge weight; and (d) directed network or digraph.

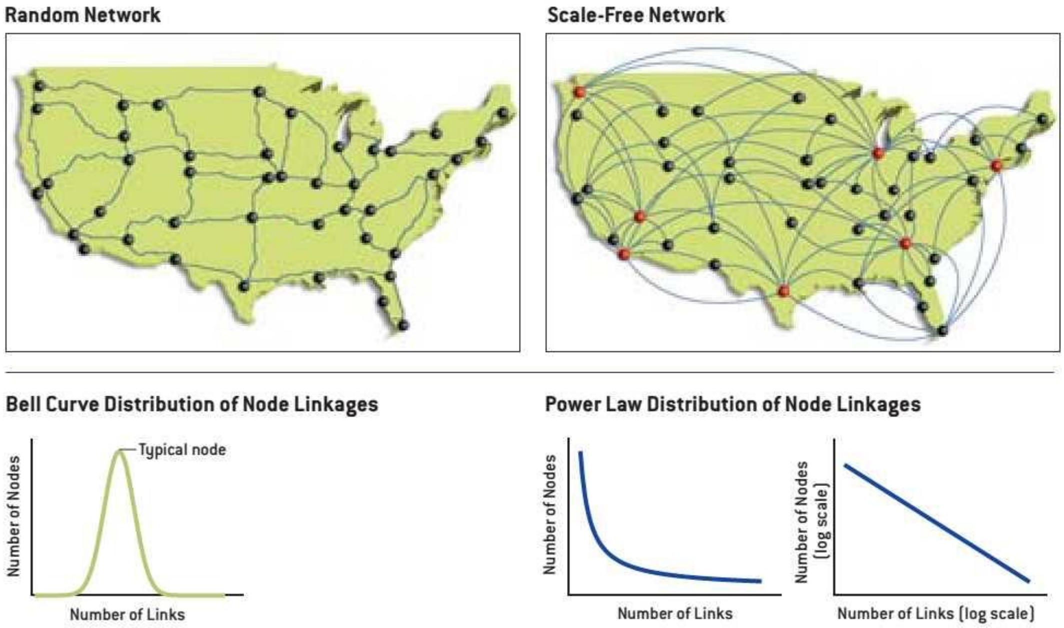


Source: extracted and modified from Newman (2003:171).

Beside those mentioned above, networks may be divided into two types: the random ones and the scale-free ones (Figure XXIX, upper maps). Random networks are systems with an apparent homogeneous distribution of nodes. Despite their random distribution, they are nonetheless democratic, each node having approximately the same number of links (BARABÁSI & BONABEAU 2003:63). Differently from the random networks, scale-free networks are dominated by a few number of nodes connected to several other different sites. These nodes are called *hubs.* Some *hubs* are nodes with an unlimited number of connections (BARABÁSI & BONABEAU 2003:62).

Another difference between these two types of networks concerns the distribution of node linkages. Random networks follow a Poisson distribution with a bell-shaped curve. Thus, the probability of *K* nodes connections decreases exponentially as *K* increases (Figure XXIX, *downward left*). Scale-free networks, in turn, follow a Power-law distribution, being the probability of *K* nodes connections proportional to $^{1}/_{K^{n}}$ (Figure XXIX, *downward right*) (BARABÁSI & BONABEAU 2003:62/3). Thus, if an accidental failure happens in the network, the random ones crack the system into isolated islands while the scale-free networks don't, because they are more robust, due to the Power-law distribution. But, in contrast, scale-free networks are highly vulnerable to a coordinated attack against their hubs (Figure XXX) (BARABÁSI & BONABEAU 2003:67).

Figure XXIX: the random network (*upper left map*) resemble the map of the U.S highway system and the scale-free network (*upper right map*) resembles the U.S airline system. Hubs are represented by red nodes. Distribution of node linkages (*downward graphs*).

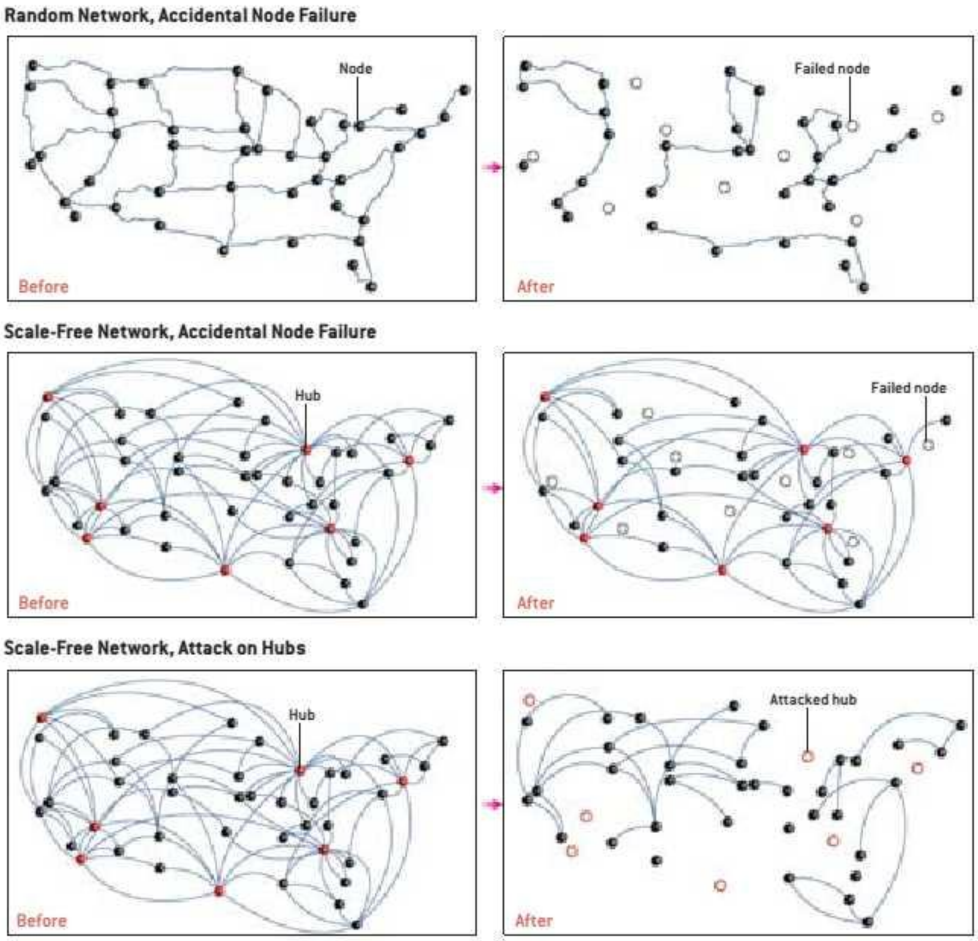


Source: Barabási & Bonabeau (2003:63).

The majority of networks are not random graphs (NEWMAN 2003:180). For instance, cellular metabolism, Hollywood stars, internet, protein regulation, sexual relationships, World Wide Web, among other examples, do not form random networks (BARABÁSI & BONABEAU 2003:74). These scale-free networks possess some features in common: the small-world effect, transitivity, degree distribution, network resilience, mixing pattern, degree correlation, community structure, network navigation, among others (NEWMAN 2003:180-196). These features suggest that there may exist a mechanism involved in the structural conformation of those networks and that it is possible to explore their structure in order to achieve certain goals (NEWMAN 2003:180). This is precisely the main idea embraced by this heuristics, to use graph theories to help unravel mechanisms.

In order to achieve such goal, there is one feature of scale-free networks that must be highlighted, the community structure. In some networks there are groups of vertices that are highly connected within a given community, and poorly between distinct communities. For instance, a community in World Wide Web suggests interaction with web pages; communities in metabolic or neural networks may suggest functional units; and communities in food webs may suggest subsystems within ecosystems (NEWMAN 2003:193). The standard procedure to identify community structure is *cluster analysis* (hierarchical clustering) for establishing "connection strength" for the vertex pairs. Notwithstanding, there are other methods to extract similar information from a network, for example, network clustering, data clustering, block models, structural equivalence, etc. (NEWMAN 2003:193-195). Such techniques may help to achieve the two goals of this heuristics.

Figure XXX: Network accidental failures.



Source: Barabási & Bonabeau (2003:67).

This heuristics is also supported by Darden's (2006) defense that one of the strategies to create a mechanism model concerns the schema instantiation. This strategy uses, by analogy, an abstract mechanism that will be further specified and instantiated. This instantiation is the process of furnishing a value to the scheme variables.

One can always ask about the advantages of developing a network – which is already a model – that will have to be further developed employed other heuristics in order to create another model. Wouldn't be more prolific (using less time and energy) to just create a network instead of undergoing all the heuristics and ending up with two models? In fact, it does not look like a benefit. Notwithstanding, the network model solely does not provide the same information as all the heuristics set does, as it may lead to the elucidation of the mechanism by which the phenomenon occurs. Networks provide information about interactions among components and may even suggest causal relation. Nonetheless, it cannot explicitly inform how the mechanism triggers the production of the phenomenon, as the heuristics set can. However, networks can help identify groups of enabling conditions and the hierarchical structure.

According to the modeler, this heuristics helped identify and isolate clusters to understand their relevancy to the phenomenon. Its use allowed to evaluate the most tested hypothesis, with larger empirical basis, besides being a way to derive new hypotheses considering a cohesive core of ecological processes that are relevant to explain different dimensions of functional diversity:

> Because it is a complex phenomenon, it is assumed that multiple drivers interact in different scales of space and time to have this phenomenon as a result. This heuristics allowed me to diagnose crucial relations in the emergence of the phenomenon, in order to extract from the larger set of relations between the drivers those "sub-frames" that indicate the key properties of the ecological system in question. The detection of these clusters allowed me to point to a feedback loop that counts in favor of the argument of functional diversity in agricultural systems. The best example in which we can perceive this is in counterpoint to the idea of Garibaldi et al. (2015), an article that deals with the main functional traits of bees that must import in the pollination of several agricultural crops in several parts of the world (39 agricultural crops to be more exact). The authors conclude that functional diversity would not be the most important predictor, but rather a particular set of functional traits that would lead to a "perfect match" between crop requirements and these bee species: the so-called matching traits. Should we abandon the idea of maintaining a diversity of functional traits in agricultural systems? My argument is that we should not go that way. I think these matching traits may be what matters most in pollination of these crops, but they may not be the most important in pollinating a huge diversity of plants in the native environments around these crops. Another set of bees (with their specific functional traits) can be crucial for the maintenance of these native plants, maintaining even the possibility that those in the crops feed on the periods when there is no floral resource in these crops. The basic idea here is: increasing the functional diversity increases the probability of different pollination systems being attended. This increases the chances of a large number of bees remaining in the vicinity of the crops, since it will have more floral resources, being a subset of these bees (and their matching traits) necessary to maintain pollination in these crops. Notice that the system feeds back into a cohesive cluster that tells a lot about the chances of this system staying over time. The determination of this cluster in the model is a fundamental step in favor of maintaining a hybrid system that gives space to reconcile the agricultural practice with the maintenance of remaining natural or semi-natural areas [COUTINHO, *personal communication*].

Despite the importance asserted by the modeler, it was not possible to verify whether the researcher have constructed such networks to achieve the heuristic goals or whether these cluster were identified by other sorts of graphs, as exposed in Figure XXIII (Sect. 4.1.4). Nonetheless, such derivations of new hypotheses demonstrates that this heuristics also fits the CIT in the contextual theory of scientific understanding (Sect. 1.2.2), according to which there exists intelligibility when the modeler is capable of deriving consequent hypotheses without performing exact calculations.

4.1.8 External Regulatory Agents

It is the identification of the variables that are external to the phenomenon but nonetheless exerts indirect influences on it. Such influences may be related to boundaries delimitations.

In this heuristics the intent is to expose those variables that possess an indirect influence on the mechanism, which are external to the phenomenon but nonetheless have ancillary or collateral effects on it. Even though these variables do not show a clear causal connection, they still can help to clarify mechanisms boundaries and delimitations, because they can provide a clear visualization of inputs that are important to influence the system dynamics. Both features of ecological system and externalities are important to the explanation of phenomena.

These could be treated as non-causal correlation situations, in terms of the confounding problem and the masking problem. The confounding problem suggests that the correlation between *A* and *B* may be attributable to some other variation in *B*, rather than variation in *A* (CLARKE *et al.* 2013:745). The masking problem, however, concerns the supposition that there exist evidence of a mechanism linking *A* to *B*, and it is possible to trace the mechanism or the process. Nevertheless "finding the mechanism linking *A* to *B* does not prove that there are *no other mechanism operating*" (CLARKE *et al.* 2014:350). Thus, this heuristics enables to recognize or suggest some features, aspects or conditions that might be involved in the mechanisms, but there are no explicitly clear evidence of such. It is assumed, then, that the 'external regulatory agents', as suggested by Bechtel (2015), are the same as the 'bottom out activities' of MDC (2000) and 'externalities' of Glennan (2002). As Bechtel writes:

> The parts and operations taken to constitute a mechanism responsible for a given biological phenomenon are often found to have a multitude of causal interactions with entities and activities initially taken to be outside the

> mechanism. Whereas [FIGURE XIX] suggests very sparse causal relations crossing the boundary-involving what are often regarded merely as inputs and outputs- there are frequently so many interactions that the practice of designating discrete mechanisms is called into question. When represented in a graph theoretical manner, the parts and operations can be seen as entities within large networks that are also scale-free in the sense that there is not a well-defined scale on which to characterize the boundaries of the mechanism within the network (BECHTEL 2015:2).

When looking toward this heuristics at the beginning of the heuristics application, it was possible to address questions such: why is it important to identify such variables if there is not enough proof of their causal connections; and why try to reveal such variables where the amount of data is so huge that it is almost impossible to perceive an actual causal relation between them? Perhaps there is no solution for this, maybe because there is not enough information about this subject, which could also be due to lack of studies or specialized instruments that may allow pursuing this correlation. Nonetheless, even when this situation is true, it is a great indicative of issues future studies should address. This was the situation in the case study. At a first look there was no recorded evidence of the modeler applying this heuristics. It was only possible to perceive their use when the *explanans* and *explanandum* were modified in their ultimate definitions, as we argue below.

An important aspect of the phenomenon that is exposed widely in ecological literature is how the response and effect traits are related to mechanisms of bee pollination maintenance in agricultural systems. The most important of these response traits for bees are sociality, nesting placement, brood parasite, body size, diet breadth, and tongue length (BARTOLOMEUS *et al.* 2017). These treats have some correlation to bees and the intense use of soil. Notwithstanding, a great deal of this literature does not establish clear links between the response traits and the ecological processes that occur in agroecosystem with the pattern of richness and abundance. Whenever these relations are done, generalizations are not possible to be made because diverse features are usually left aside and this masks the effects of possible trade-offs and synergies. The features that are responsible to mask the effects are external regulatory agents. The relevant issue about his heuristics is to show that mechanisms, models and relations are not only determined by causal relations that are direct and clear of the system components, but also by other factors that are in some way not known, or not yet established, and have influence on the phenomenon and help to develop some boundaries of the latter (COUTINHO 2018:*manuscript*).

The use of this heuristics became clearer as the modeler developed his theoretical model. In doing so he adopted a notion of function that presupposes the ecological system as an integrated system, consisting of minimally decomposable systems that are not possible to be understood only through the individual observation of parts (NUNES-NETO *et al.* 2014). As this notion starts to be a key principle to guide the visualization of the system by the modeler, two properties are, therefore, adopted: closure of constraints and closure of processes. The first one indicates that all the fundamental components of the investigated system exert some level of constraint on the other components with which they interact, and are themselves the target of constraining processes. In turn, the second property indicates that these components are related to certain actions that contribute to the emergence of the phenomena of interest. Integrating the two properties it is possible to understand that non-stochasticity in the space-time position of the components is an important requirement for the understanding of an integrated system.

4.1.9 Changes in Operational Components

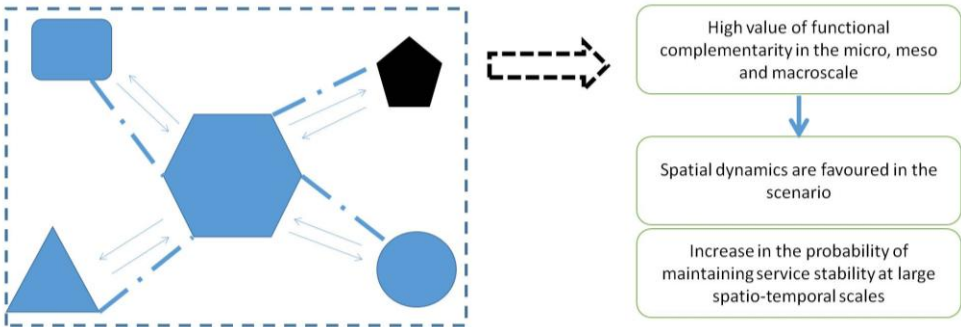
It aims to explore alternative scenarios and predict possible courses of the system under investigation by modifying the operational components.

This heuristics was created after the ultimate sketches, and it was the only one created solely by the modeler. It aims to explore alternative scenarios and predict possible paths of the system under investigation. This may be achieved by modifying some elements of the enabling conditions chart. Therefore, this heuristics gives the chance to alter some system attributes (for instance, diversity traits) beyond those usually proposed by the empirical literature, in order to interact with wider ecological frameworks and reflect on a diversity of scenarios, such as the four examples described below.

In Figure XXXI the modeler creates a predictive schema combining two of the main scenarios in the metacommunity theories: species sorting and patch dynamics. In this layout the patches are well connected and present high structural complexity of the vegetation. In this case the agricultural activity has been recently introduced in the system; hence, the high supply of resources and lack of history of previous suppressions.

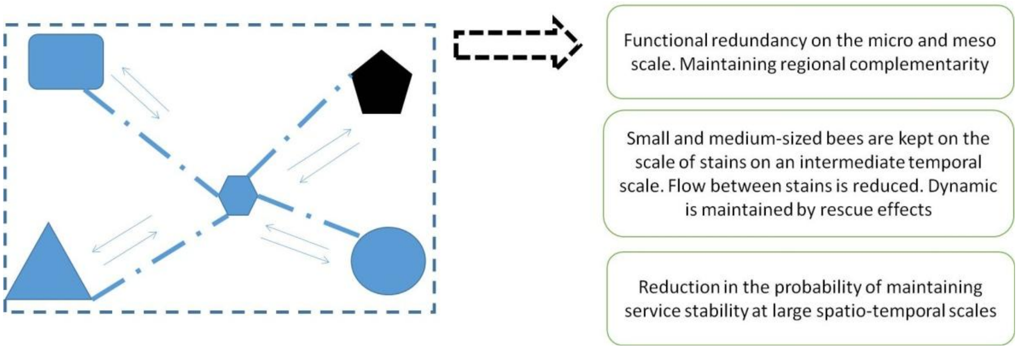
The schema presented in Figure XXXII combine the species sorting scenario with the mass effect scenario. In this case the prediction is that the distance between fragments will be increased and the remnant patches will serve as strongholds for some groups. The landscape will act as a filter for the dispersion of some groups. At the local scale structural characteristics and selection on some groups according to their response traits will be maintained, for instance, impaired pollen flow between patches of vegetation where the croups will be favored by groups present in the remnant patches.

Figure XXXI: Schema representing a system where the scenarios of species sorting and patch dynamics are combined.



Source: Coutinho (*personal communication*).

Figure XXXII: Species sorting combined with mass effects scenarios.

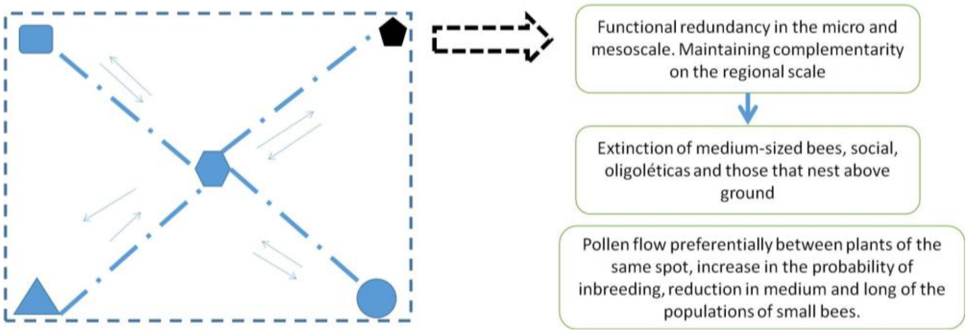


Source: Coutinho (*personal communication*).

Figure XXXIII suggests a different plot combining the same scenarios, species sorting with mass effect. The distinction is that in here there exists the predominance of agriculture at the scale of the landscape and the remnant patches will serve as strongholds for small bees. The extinction of landscape will act as a filter for the dispersion of bees. At the local scale the structural characteristics which will select non-soil, oligolectic and small bees due to their response traits will be maintained. The larger bees will be responsible for a large part of the pollen flow between patches, increasing the chance of service stability at the meso- and macroscale. Some groups of crop plants will still be favored by the presence of large bees.

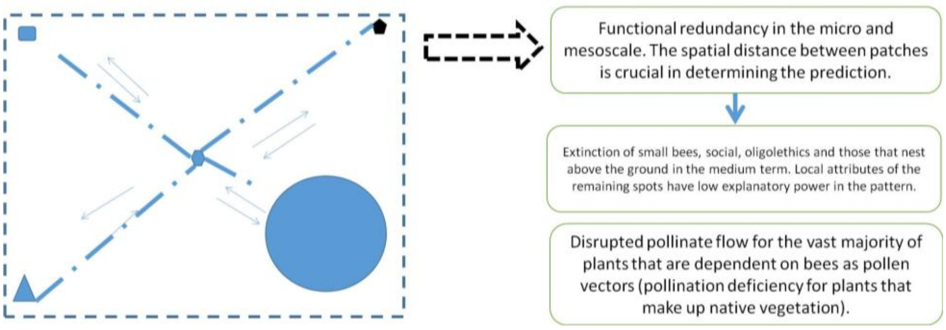
In the schema of figure XXXIV, the prediction is only made based on the specie sorting effect. In this scenario, there will be predominance of agriculture at the scale of the landscape with abrupt reduction of the area of several remnant patches. These patches will serve as strongholds for small bees at the small spatial scale of resolution, being the most decisive in the maintenance of these groups. Disruption of spatial processes and extinctions will work as a filter for the dispersion of these bees. At the local scale structural characteristics selecting honey bees with small response traits that nest in the soil will be maintained. This will lead large bees to extinction, damaging the stability of the service at the meso- and macroscales. The crops will undergo pollination deficiency due to the marked decrease in the number of functional types of pollinators. Therefore, the system will collapse in the medium term.

Figure XXXIII: Species sorting combined with mass effect scenarios.



Source: Coutinho (*personal communication*).

Figure XXXIV: Diagram representing a species sorting scenario.



Source: Coutinho (*personal communication*).

Scientific explanation in the ecological realm must possess a predictive nature (explanatory and anticipatory) if it is to be of use in management. Predictions must be based on a theoretical framework (explicit or implicit) that is decisive for its aims and limitations (on the absent of a theory no prediction is possible). Thus, it is asserted that the understanding of process responsible for the phenomena of interest not only helps in the construction of explicative models but also contributes to their predictive accuracy (MOUQUET *et al.* 2015:1297). This assertion is aligned with one of the epistemic goals of science, namely prediction. In the contextual theory of scientific understanding, the ability to predict, that is, to recognize qualitative consequences of the theory, means that the theories are intelligible for the scientists (DE REGT 2017). Thus, in this case study the understanding assessment also fits CIT: A scientific theory *T* (in one or more of its representations) is intelligible for scientists (in the context *C*) if they can recognize qualitatively characteristic consequences of *T* without performing exact calculations. CIT has been corroborated by this heuristics in our case study.

4.1.10 Mechanism schema

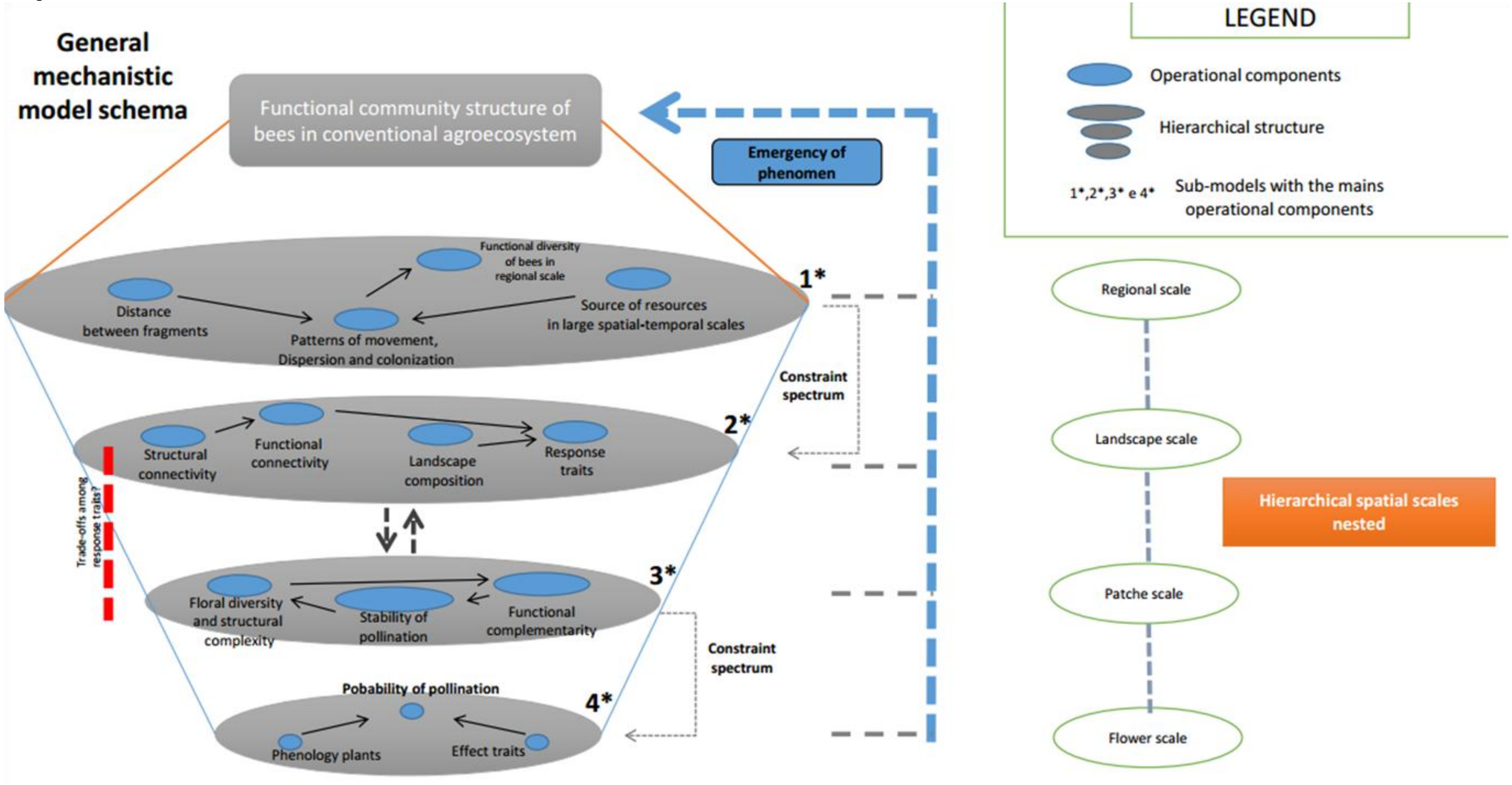
It is the conceptual model obtained after the use of the heuristics above.

According to Craver & Darden (2013:31), "a mechanism schema is a description of a mechanism, the entities, activities, and organizational features of which are known with sufficient detail that the placeholders in the schema can be filled in as needed". The substantial difference from a mechanism schema to a mechanism sketch is that the second one is a draft that helps to construct the schema-model, and will be discarded eventually. Thus, this heuristics aims to expose the mechanistic model that was created after the application of all previous heuristics and will be described in the following.

In Figure XXXV, the image on the right side indicates the main spatial scales that influence the pollination services: regional, landscape, patch, and flower scales. This image clearly shows how the application of the heuristics hierarchical structure led to the identification of a structured spatial system containing four scales.

The image on the left side represents the operational components at each level: 1* indicates ecological components and processes that occur at a regional scale and provide the regional pool of species that operate at the more restricted spatial scales; 2* includes aspects of the structure of the landscape that influence the functional composition of the bees through the interaction with certain response traits, which are the traits that condition the response in richness and abundance to these spatial attributes of the landscape; 3* contains structural characteristics of habitat patches that influence the probability of more or less complementarity of traits at this scale, influencing the space-time stability of the pollination service; 4*, the finest scale used in this model, indicates that pollination success will ultimately depend on plant phenological attributes (supply of resources compatible with the needs of bee communities, for example) and effect traits (traits of bees related to the successful transfer of pollen grains). Even though the modeler called this system nested, this claim requires future disambiguation on how scientists may differ from a system that is nested from a system that is linear, according to their frameworks and visualization schemes.

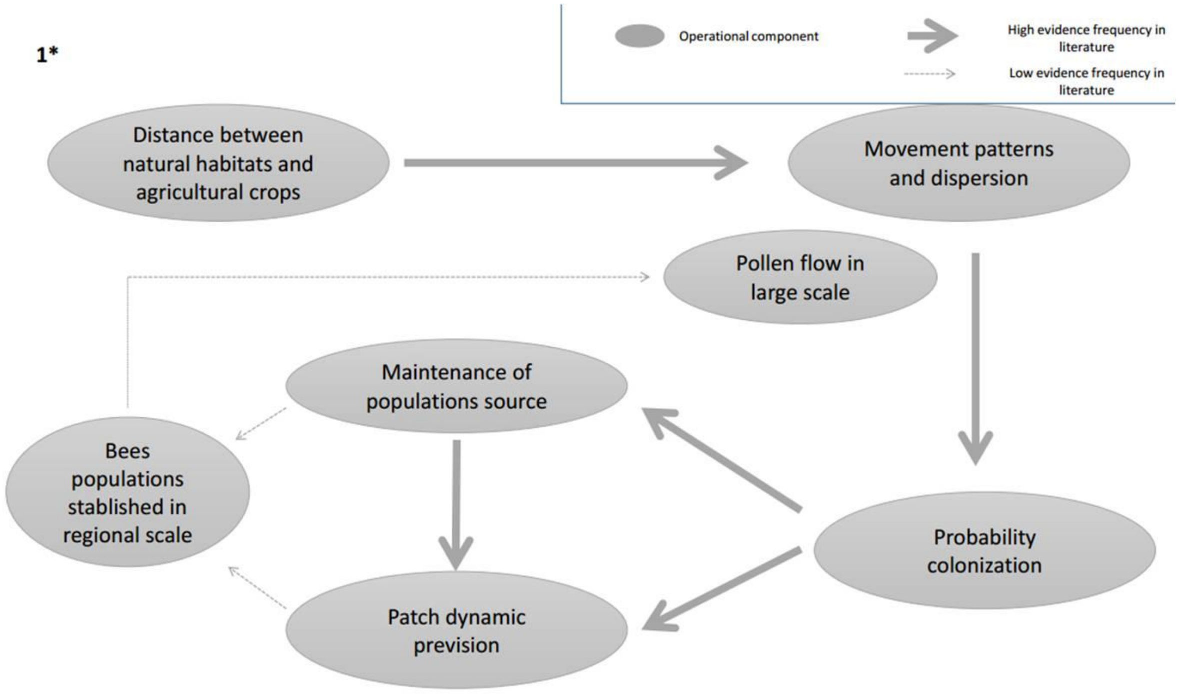
Figure XXXV: General mechanical hierarchical model indicating the main spatial scales of influence on the service of pollination with the respective operational components.



Source: Coutinho (*personal communication*).

We can now zoom-in at each system level. Figure XXXVI represents what the modeler calls a mechanistic sub-model, and indicates the ecological processes that occur at the regional spatial scale. For instance, the distance between natural habitats and crops influences the patterns of movement of bee species in space. This generates consequences to the probability of colonization of the patches, which will influence in the chances of maintaining viable populations of bees that promote pollinic flow over large territorial expanses. The effect on the network will be conditioned by the response traits that the bee communities present in this spatial area. Such predictions consider the assumptions derived from the patch dynamic model (from metacommunity theory), considering the probability of trade-off between colonization and competition in the different habitat areas.

Figure XXXVI: Mechanistic sub-model at the larger scale.

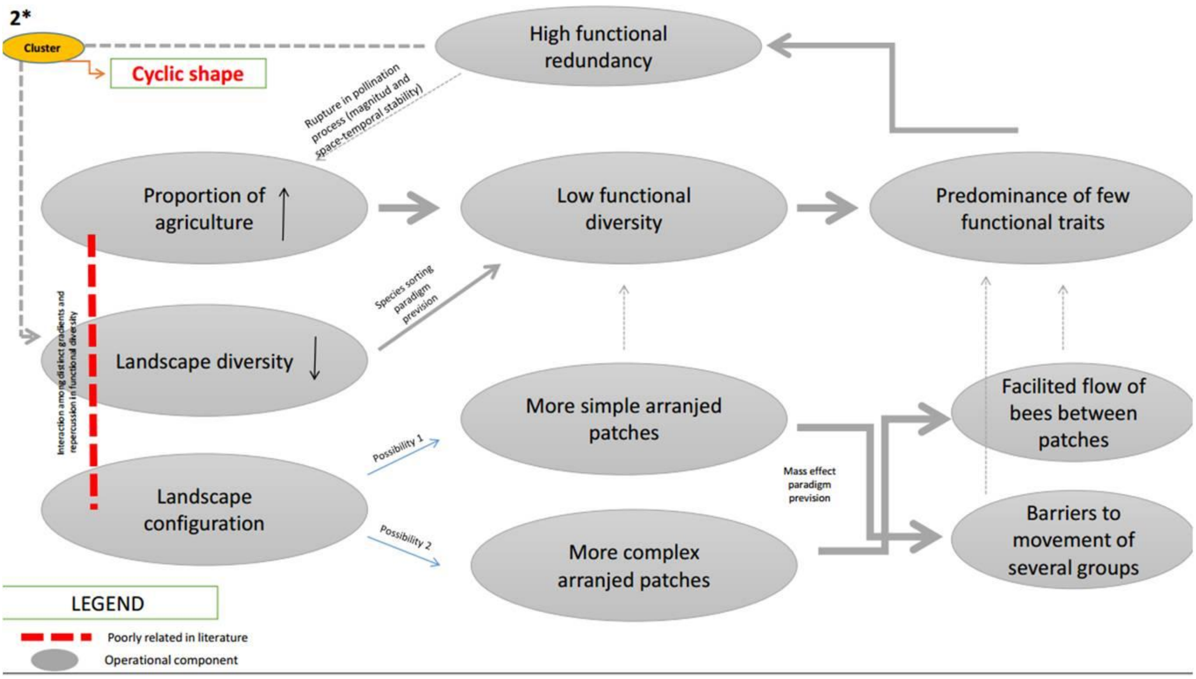


Source: Coutinho (*personal communication*).

In this sketch the heuristics 'evidence frequency' is represented by the arrows. Even though there is no explicit information exposed by the modeler on how frequent each of these relations between the operational components occurred, the solid arrows show high evidence frequency in the literature, and the dotted arrows represents low frequency of evidence in literature.

In the schema of the second scale, the landscape scale (Figure XXXVII), the mechanistic sub-model indicates ecological processes that are predominant under intense agricultural regime and low landscape diversity. Together this structure leads to a simplification of the pool of bee response and effect traits that would contribute to the increase in the diversity of the landscape (according to the species sorting model), via pollination process. The low functional diversity in these systems leads to a cyclical process that maintains the landscape structure with these characteristics. The landscape configuration affects the pattern of movement of bees between the habitat patches of this agricultural landscape (according to the mass effect model). But regardless of the degree of complexity of this configuration (high or low) the system is conducted for the same cycle, since functional diversity has been reduced to a critical level.

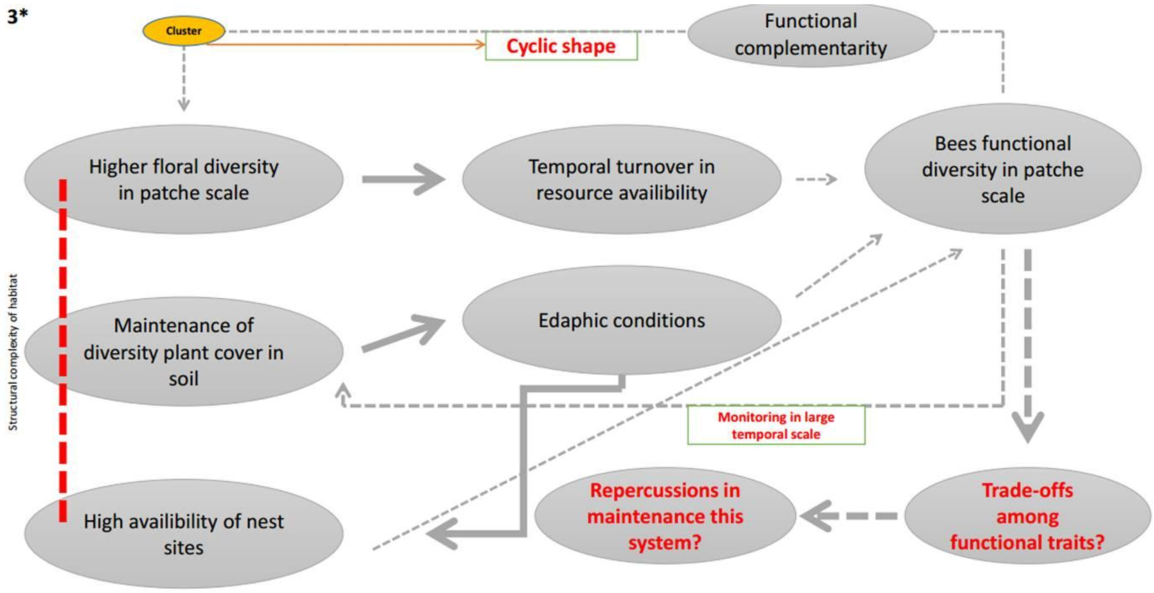
Figure XXXVII: Mechanistic sub-model at the landscape scale.



Source: Coutinho (*personal communication*).

Figure XXXVIII represents the third scale of the system, that of the habitat patches. According to the species sorting model predictions, the high diversity of plants, floral resources and different types of cover in the soil would promote in the medium and long term a high functional diversity of bees in this patch (through complementarity of niches). By means of positive feedback mechanisms, this system is cyclical and contributes to the increase of the stability of the pollination service at this scale. Issues that have not yet been reported in the empirical literature are related to the possible mechanisms of trade-offs that may exist between response and effect traits and the potential impacts that such trade-offs might have on the maintenance of this system.

Figure XXXVIII: Mechanistic sub-model indicating ecological processes that occur at the spatial scale of the habitat patch.



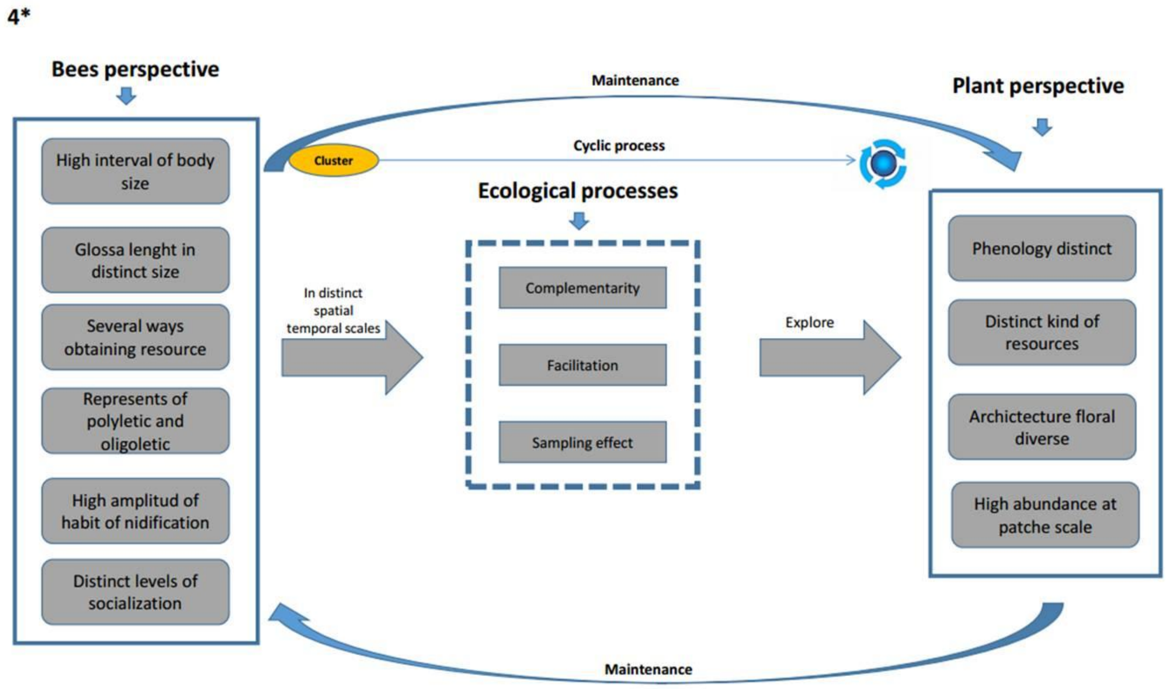
Source: Coutinho (*personal communication*).

The fourth and smallest scale of the system is shown in Figure XXXIX. The ecological processes indicated occur at the spatial scale of the interaction between the community of bees and the plant community, focusing on their functional attributes. Different combinations of response and effect traits of the bees, associated to a high supply and diversity of resources along time, contributes to a cyclical process of maintenance of these communities. Interaction between bees and plants occurs through the processes of functional complementarity, facilitation and sampling effects. The evaluation of specific combinations of traits and their influence on the successful pollination of native plants is a subject rarely explored in the empirical literature, which needs further investigation.

A reflection on this heuristics can be outlined: is the mechanism schema a heuristics itself or is it the product of the heuristics set? If the developed schema is the model *per se* then it cannot be a heuristics because it is already the product of the heuristics set. However, if the developed model possesses more than one mechanism then it can be a heuristics because it will possess two, three, four or more schemas within the model, even though this model is the model *per se*. Another important point to highlight is that the application of the heuristics was not only shaped by its theoretical foundation but also by its pragmatic limitations. In the modeler words, this heuristics

> […] is the moment when all of our effort can be visualized in an organized representation of everything that has been considered throughout the other heuristics. This is the moment of synthesis and choice of the best communication strategy for our readers. Here is the challenge of representing scales, clusters, drivers and their most relevant interactions in explaining the phenomenon. A key skill has been developed here which is that of objective scientific communication. Communicating a complex phenomenon through the use of this heuristics is the "last step" of this endeavor, which will allow us to ask three questions and answer them by looking only at this representation or responding in large part to a good analysis of this scheme. Question 1: what phenomenon are we trying to explain?; Question 2: What is most relevant in terms of scales and processes to be considered in this explanation?; Question 3: What are the main explanatory messages I can draw from this template? Answering these three questions well, I think we did a good homework (COUTINHO, *personal communication*).

Figure XXXIX: Mechanistic sub-model indicating ecological processes that occur at the spatial scale of the interaction between the community of bees and the plant community.



Source: Coutinho (personal communication).

This is a very relevant point because the idealized theoretical heuristics sometimes had to be modified in the empirical context of our case study. Such modifications occurred on the account of the modeler’s background knowledge and of the level of complexity the phenomenon exhibited. For instance, a usually expected behavior during the process was the adaptation of the uses of the heuristics and the abandonment of several sketches. According to this, it is not a surprise to inform that this same heuristics, mechanism schema, at some point of the heuristics utilization, model development and explanation construction, was also discarded. This happened because the goal of the modelers’ research was no longer to create a mechanistic model of the pollination service in agricultural systems but to develop a conceptual framework that could unify theories from complex systems sciences, mechanistic explanation literature, and metacommunity theories. Even though the schema was no longer used by the modeler, it was nonetheless an important step in helping him make his framework intelligible.

Even though the schema was discarded when compared to the final theoretical model built by the modeler, it had an important epistemic value in assessing his understanding of the phenomena. One can agree with De Regt (2017) in that visualization has to be learned, visual skills need to be developed and refined in order to apply them fruitfully. This is also corroborated by the modelers' statement that the effort of transforming his theories into visualizable models made him face theoretical divergences, therefore improving his skills.

4.2 Heuristics as display

The core idea of the Contextual Theory of Scientific Understanding (CTSU) gravitates around the intelligibility of a theory[17]. The CTSU has the benefit because it elaborates on variations in standards of intelligibility:

> Intelligibility [is] the value that scientists attribute to the cluster of qualities of a theory (in one or more of its representations) that facilitate the use of the theory (DE REGT 2017:40).

Thus, a theory may be intelligible in different ways and this is only possible because theories are historically content- and context-dependent. Thus, the more a theory is intelligible, the more chances the scientist will have to understand it. Therefore, there exist some tools that help a theory be more intelligible than others and, consequently, facilitate scientists to achieve understanding. Some of these tools are visualization, causal reasoning, visualizability, unficationist notions, mathematical index, and so on (DE REGT 2017).

Using *visualization* as a tool for understanding is a common practice in the history of science. Some authors (*e.g.* MACHAMER, DARDEN & CRAVER 2000; DE REGT 2017) attribute this to the ontogenetic and phylogenetic development of human beings, since seeing is our most important way of perceiving the world. It seems plausible that our sensory

[17] It is important to highlight that in the contextual notion of understanding, there is no difference between theories, hypothesis, and principles. The starting point is that all of them are statements, and these statements can be reliable according to its intelligibility (DE REGT 2017). This is in agreement with Giere (2004) when he says that there is no reason for such analysis because the terms 'theory', 'laws' and 'principles are used broadly in scientific practice and in metalevel discussions about sciences.

experience provides bases of intelligibility which are then extended to realms beyond sense perception, and thus scientists will be inclined to use visualization as a tool for scientific understanding (DE REGT 2017: 257-8). It is important to highlight here, that visualization is a possible tool to achieve understanding but it is not a dependent condition. Thus, in a (not so much) hypothetical situation a scientist with limited visual capability is also able to achieve understanding.

Our discussion above has shown the epistemic value that visualization had for model building in our case study. According to Bechtel & Abrahansem (2005), diagrams of complex mechanisms are preferred to theoretical representations because they can inform the spatial organization of mechanisms, making it easier to track. De Regt (2017:258) points out sharply that this does not mean that diagrammatic reasoning can be applied easily and immediately and this is perfectly reflected in our case study. When looking at the heuristics 'mechanism sketch' (Sect. 4.1.2), 'hierarchical structure' (Sect. 4.1.3), 'changes in operational components' (Sect. 4.1.9) and 'mechanism schema' (Sect. 4.1.10), one cannot deny the important role they had in the elaboration of the model, and, therefore, in the construction of explanation. This is also confirmed by the modeler's statement reproduced in section 4.1.2, where he states:

> In the first proposition of the "mechanism sketch" I realized that I could not arrive at a minimally reasonable scheme of communication of my phenomenon and of the relevant variables for such. […]. With each new sketch, new challenges, and solutions, two dimensions of the process of construction of scientific knowledge that led me to lead a process of full immersion in the scientific literature to address the gaps that were gradually perceived. Each new reading enables me to review my sketches (often not materialized, but purely mental), and I will reaffirm my understanding of my phenomenon and the potential contributions that this research can provide [COUTINHO, *personal communication*]

In this sense one can agree with Morgan and Morrison (1999) that models can work as tools for the improvement of theories. In this specific case study I must assert that the visualizability had a fundamental role for the scientific understanding at model construction, even though this role was provisory when compared to the final framework put forward by the modeler. Another confirmation of the power of this conceptual tool is stated by the modeler regarding precisely the shape of the mechanism:

> In wider theoretical models, the general format of the mechanism, when dealing with a more complex structure, [also] contributes. In this way, […] it allows to identify the format of the frame of relations of the mechanism, which can even be a hybrid of different forms. The relationships can be

> cyclic, linear, ellipsoids or a hybrid of these forms depending on the cut-out analyzed. The definition of the typology is crucial in understanding the magnitude that certain processes may have in generating patterns of bee functional diversity. This heuristics [typology of shape mechanism] pointed to a core of hypotheses that need an empirical evaluation with great potential to generate advances in the understanding of the relation between functional diversity aspects and ecosystem properties [COUTINHO, *personal communication*].

The unificationist conceptual tool brings an interesting aspect to discuss about the biological field. Biological sciences are extremely disunified, presenting a diversity of epistemic cultures (LEONELLI 2009). The knowledge produced possesses various forms: mechanistic, causal reasoning, historical narrative, descriptive, functional, mathematical, representational, and categorical (*ibid.* 2009). As the nature of the data and the methods of analysis are so diverse, it is not a strange practice that scientists try to solve this puzzle in a piecemeal manner. This was exactly what happened in our case study. For instance, consider the enabling conditions board shown in section 5.1.3. It is perceivable the variety in the nature of the data, being each of them collected with a different instrument and strategy, and therefore analyzed in accordance. The idea of this table was to put all this information together to realize how they function in the pollination service in the agricultural system. In addition, there was also the effort to combine different theoretical propositions, as stated by the modeler:

> […] It is no novelty that ecological phenomena are hierarchical and that there are several levels of interaction between scales in the hierarchy, which may be spatial, temporal or spatiotemporal. This heuristics [hierarchical structure] was applied when I understood the potential that two metacommunity models could help me in proposing our conceptual model. I realized here that both could make great contributions, provided I used the most appropriate scale in using the forecasts of each of these models. THEY COULD BE COMPLEMENTARY IN THE EXPLANATION OF THE PHENOMENON. It was here that I realized that the discourse of plurality in scientific explanation was fully consistent with my phenomenon: it was all a matter of scale […] [COUTINHO, *personal communication*, emphasis added by the modeler].

It is undeniable that the unificationist tool played a major role in the development of explanation and model construction. Nonetheless, the question about whether this notion helped in scientific understanding still lies. What is defended here is that the unificationist notion has, by its own nature, the capacity of embrace the other conceptual tools. Thus, these tools, once embraced, do functioned as triggers for the understanding process to happen? The answer is yes, even though scientific understanding by means of unification happened in a different manner than those by conceptual tools.

According to the modeler's testimony quoted in section 4.1.2, the sentence *"In the first proposition of the mechanism sketch I realized that I could not arrive at a minimally reasonable scheme of communication of my phenomenon and of the relevant variables for such*", also enables us to make inferences about what MDC (2000) call *productive continuity*. The continuity for MDC concerns the causal relations between the elements of a mechanism that enable it to produce an event or byproduct (*i.e.*, the phenomenon) and can be easily tracked as a conceptual tool. In our case study, the modeler was not able to perceive such productive continuity in the first sketches due to several gaps that existed in the ecological literature. The fulfillment of such black and gray boxes, when possible, was only due to his knowledge about the mainstream literature in ecology. Whilst this happened, as perceived in his more detailed schema, the understanding of his phenomenon was becoming more apparent. Thus, causal reasoning led him to understanding because it revealed what was for him the underlying structure of the world:

> […] I cannot construct a conceptual model if I do not know the set of variables and conditions of interaction between these variables that are relevant in the proposition of this model. This does not mean that we should be able to begin the proposition of the model by knowing all the relevant variables - this would take away one of the great virtues of the art of modeling: a gradual refining of our theoretical constructs about the functioning of the world. This heuristics [enabling conditions] is the backbone of this work since it allows a constant search in the literature for ecological variables (drivers) of paramount importance in explaining the phenomenon and its zones of intersection and influence. I used three great pillars to derive these fundamental drivers. In my immersion process, I saw the great advantage and relevance of what I could do with these great pillars. What I was proposing was innovative and of great interest to ecology: to bring out the most relevant ecological processes to explain the functional diversity of bees in agricultural systems, highlighting the most relevant spatiotemporal scales in the explanation of this phenomenon, through a meticulous study of literature, re-evaluating these agricultural systems from a complex systems perspective, using the theoretical-methodological framework of mechanistic explanation literature. The choice and forms of interaction between these variables are not always so solved in Ecology. The great thing we have done is to arrive at a more satisfactory level of explanation (seeking to reduce the existing gaps) as we seek the intersection of these great pillars, looking at spatial and environmental drivers along with attributes of the life history of the chosen biological model (Functional diversity of bees). This heuristics "opened my mind" to a more critical view in the ecological literature, searching for variables of paramount importance for the proposition of the model (COUTINHO, *personal communication*)

Grasping the productive continuity of the mechanisms allowed the scientist to produce predictable models that are reflected in the heuristics 'changes in operational component' (Sect. 4.1.9). This is in accordance with De Regt's (2017) assertion that causal reasoning enhances the scientist's ability to predict how the systems will behave under particular conditions. In Woodward's (2003) account, scientific understanding can also be achieved by answering questions about the behavior of the system investigated. Even though there are different standards for intelligibility, De Regt (2017:106) suggests the following criterion:

> **CIT:** A scientific theory *T* (in one or more of its representations) is intelligible for scientists (in context *C*) if they can recognize qualitatively characteristic consequences of *T* without performing exact calculations.

One of the main virtues of variations in standards of intelligibility is that one can accommodate thus the manifold ways in which understanding is achieved in scientific practice. According to this notion, if scientists understand a theory, the theory is intelligible to them, and this was exactly what was perceived in our case study.

4.3 Final considerations

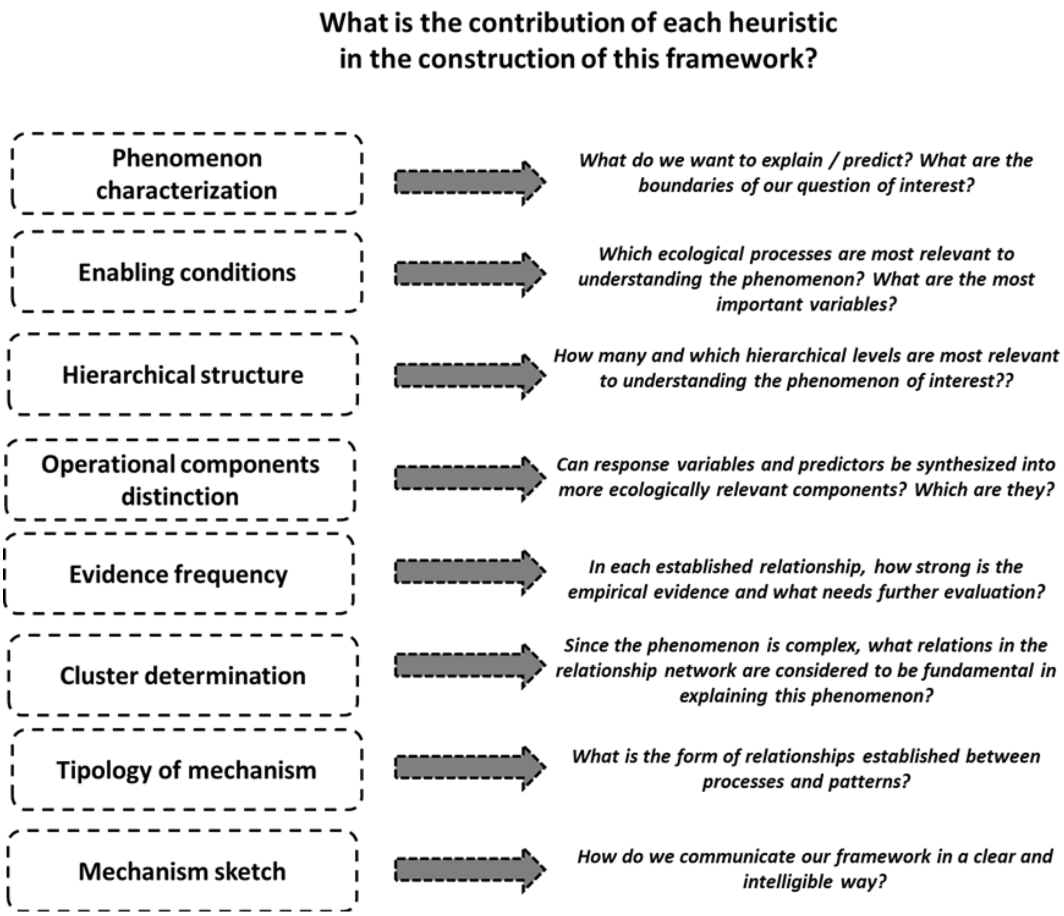
As exposed in this chapter and represented in previous diagrams, it is explicit that the application of the heuristics occurred at several moments during the process of model development, even though the mechanistic model was later discarded. Not only the sketches were target of changes or modifications, but the whole set of heuristics. It is important to remind at this moment that the heuristics set influenced the scientist practice, but his practice also shaped the heuristics framework. This feedback relation was so intense that by the end of the model construction the heuristics were perceived by the modeler not as actions anymore, but as questions to be answered (Figure XL).

This raise questions such as: why did the modeler discard all the schemas? Is it possible to visualize the mechanistic literature in his theoretical model? And, was the mechanistic literature a necessary foundation for his model or only a provisional one? When one looks to the modeler's conceptual framework (Part I, Box 1), the impression is that the mechanistic literature played only a temporary role in model construction, but when one looks to the process of model construction it is clearly noted that the mechanistic literature had a major role in the scaffolding required to develop the theoretical model. And this is reflected in its gradual increase of complexity in the modeling practice.

Such behavior reaffirms the idea that the heuristics functioned as epistemic tools and contributed for the scientist to achieve understanding of his phenomenon while he was constructing his explanation. For instance, Figure XL was created by the modeler and explicitly manifests the modification of the heuristics from empirical activities to mental ones.

This strongly suggests that the results of the heuristics application had a reflective power for the modeler, daring to say that it was a continuum process of reflection which justifies all the abandonments. This reformulation gives support to the consideration that there were some features concerning the model construction that helped or triggered the scientist`s understanding of the phenomenon. His statements also gave several elements that allowed me to reassure the presence and importance of the conceptual tools of the contextual theory of scientific understanding in his model building practice and understanding achievement (Sect. 4.1 and 4.2.).

Figure XL: The contributions of the heuristics for the construction of the theoretical framework, according to the modeler's view.



Source: Coutinho (2018:*manuscript*).

The main goals of this chapter were: (i) to expose the main theoretical grounds that underlie each heuristics; (ii) to situate them in our case study by showing, whenever possible, how each of them were used by the modeler during his process of explanation development and model construction; and (iii) indicate how they correlate with the contextual theory of scientific understanding. There is still one final question to be answered: can the Contextual

Theory of Scientific Understanding be applied to scientific practice that is not a historical reconstruction? According to this case study the answer to this question is: yes, CTSU can be applied to contemporary scientific practice. Now, the remaining question is: how is scientific understanding achieved during the process of model construction? This question will be answered in next chapter.

5 EVALUATING ‘SCIENTIFIC UNDERSTANDING’: how to go a step further

In the previous chapter the heuristics toolbox was unfolded in order to expose how the scientist used it to create a model of pollination services in the agricultural system. This disclosure provided enough information to support the idea that the conceptual tools of the contextual theory of scientific understanding were in fact perceived in this scientific practice. The tools of visualizability, mathematical indices, causal-mechanical and unificationist notions assuredly were effective, each one in its own way, for the explanation development and model building.

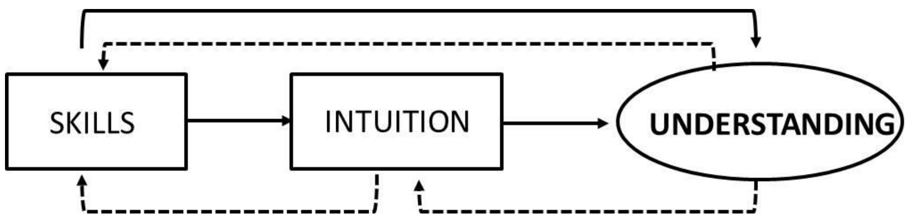
One common difference between explanation and understanding is that the last one is necessarily dependent on a subject. The information that is considered as contributing to understanding must be accessible to the epistemic agent, in other words, the “person who use the explanation must be able to know or grasp the information” (DE REGT 2017:84). Before exposing the goals of this chapter a few comments regarding this proposition adopted by the CTSU are important. First, it might look rather tautological to say that to use the explanation it is first necessary to know the information that this same explanation contains. How would it be possible for one to use the explanation without the intrinsic information? Perhaps this relates to the context of understanding in the sense that there exists some need of leveling between information and subject. The subject must, in some way, be prepared (by means of skills, theoretical background, etc.) to access the information, and therefore, understand it. But possessing these capabilities does not directly indicate that the subject, as soon as she receives the information, will be capable of understanding it. Once it is assumed that understanding is a cognitive success (PRITCHARD 2014), it is tacit that the process of understanding demands an epistemic agent, but there are probably much more processes involved in between information, explanation, grasping and understanding then the CTSU could perceive by looking at historical case studies of scientific practice. Second, it might be controversial to assert that explanation as a whole does not require an agent *per* se. For instance, if explanations are considered as final products of the scientific endeavor, then there will be no epistemic agent relations. But if it is considered as the scientific activity of building explanations, then it must have an agent. Therefore, taking these considerations into account, this thesis argues that both explanation and understanding are dependents on the subject-explanation and subject-understanding occurring at the same time.

Considering that scientific understanding and scientific explanation are content- and context-dependent, and reflect the scientific understanding that happens in the ongoing scientific process, for instance, as previously exposed through the case study, this chapter intends to extend the contextual theory of scientific understanding by adding intuition as a crucial component that mediates between skills and understanding. Other assumptions also follow: (i) scientific understanding is an instant, a temporary event achieved through gradual processes, suggesting degrees of understanding, and (ii) the heuristics toolbox helped the modeler achieve epistemic virtues by means of the improvement of his skills. These propositions helped answer the main question of Part II – how is scientific understanding achieved during the process of model construction?

5.1 The step further

One of the characteristics of the contextual theory of scientific understanding is its pluralistic view. The CTSU does not stand for a scientific understanding that occurs according to a specific model. This is in fact one of the reasons for the elaboration on different standards of intelligibility in CTSU. This section brings an instigation: it presents a model for scientific understanding (Figure XLI). Even though this model represents a very specific scientific context (making it difficult to claim generality; see LEVIN 1992), it will be an attempt to make sense of how scientific understanding was achieved in an ongoing scientific practice that used philosophy of science as an interdisciplinary counterpart of scientific inquiry. It is acknowledged that several pieces of information pertaining to each box are absent, and the overall simplicity of the model does not do justice to the complexity involved in its achievement, but this simplification it a starting point for a reconstruction of the scientific understanding process. In the following we will further explain this model.

Figure XLI: General model of understanding. Full arrow represents a direct relation between the boxes. Doted arrow represents a feedback relation between the boxes.

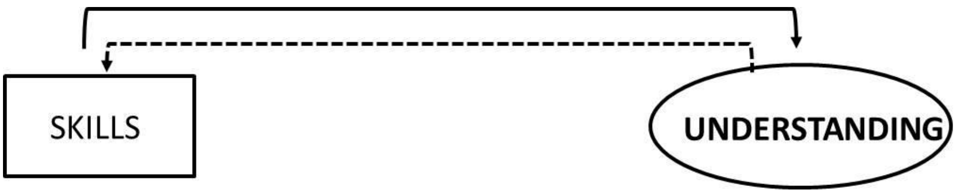


Source: Elaborated by the author.

One of the propositions defended in this chapter is that understanding is a temporary event that happens gradually. This progress over time is reflected in different degrees of understanding. The model represented in Figure XLI will be decomposed in order to better communicate what happens in each step of the process.

As previously stated, the understanding achieved in the case study occurred in distinct levels. In all levels, the scientist (S) is considered as an epistemic agent that possesses highly technical skills with a theoretical background that makes him capable of doing reliable decisions about his object of study. In the first level of understanding (Figure XLII), the epistemic skills (abilities) of the scientist are enough for him to achieve understanding of the phenomenon (upper full arrow). Therefore, these abilities work as mediators that allow the scientist to gain knowledge by means of technical effort. In some cases the understanding that is achieved is the final product, and in this model is represented as the first level of understanding.

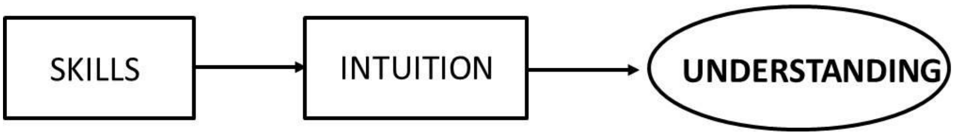
Figure XLII: Model of understanding - level 1



Source: Elaborated by the author.

In other cases, the knowledge gained from achieving understanding transforms itself into know-how for further analyses and experiments, improving in this way the scientist's epistemic skills (dotted arrow). This will prepare the scientist for the next level of understanding (Figure XLIII). This illustrates how scientific understanding is, in this model, considered as transient.

Figure XLIII: Model of understanding – level 2



Source: Elaborated by the author.

Again, the theoretical knowledge and technical know-how (combined into skills) allow the scientist grasp his phenomenon. Considering that *S* is not always in a position to causally interact with the phenomenon (YLIKOSKI 2009), the abilities (that were developed in a previous level) qualify *S* to think the phenomenon in a way that does not require laboratorial instruments for analysis. For instance, thought experiments, anticipatory understanding, etc. are strategies that do not require physical interaction with the phenomenon, and rely strongly on intuition (Figure XLIII). This is a key aspect for this model. But it is necessary, for sure, to be clear about what we mean by "intuition". To connect the CTSU with the intuition process defended here it is worthy recall,

> […] skill and intuitive judgment play a central role in the process of achieving scientific understanding. If a theory is intelligible to scientists because its theoretical qualities match their skills, they can reason "intuitively" with it. Like our everyday intuitive skills, scientists' skills are the outcome of a complex learning process in which their evolved cognitive capacities interact with the environment in which they find themselves (that is, the historical and disciplinary context of their science) (DE REGT 2017:110).

What is called intuition here is a mental action that enables the modeler to assess counterexamples. In anticipatory understanding, when the causal interaction with the object is not possible, relevant inferences may be made about future consequences of some event or series of events regarding the *explanandum* (YLIKOSKI 2009). Counterfactual situations grant, thus, predictions of the phenomenon without causal intervention by creating 'internal mental models' (WASKAN 2006), and this is consonant with the criterion for the intelligibility of a theory at the contextual theory of scientific understanding:

> **CIT**: A scientific theory *T* is intelligible for scientists if they can recognize qualitatively characteristic consequences of *T* without performing exact calculations.

Even though qualitatively characteristic consequences of *T* can be recognized through any strategies with the exception of exact calculations, this does not mean that they are strictly realized only by mental processes. In here, it is acknowledged that this procedure is only one among many others, but is nonetheless crucial to achieve intelligibility and inevitably is bounded to the important role of the conceptual tools visualizability and visualization in the development of scientific explanation.

In this sense, anticipatory understanding is considered here as a type of thought experiment, namely a counterfactual thought experiment. As any thought experiment, it deliberately and purposively appeals to imagination (DE MEY 2006). In order to avoid that this notion be slippery, one has to use it with caution (HAWTHORNE 1991) by manipulating one factor at time (DE MEY 2006). In this manner, anticipatory understanding can be a powerful tool. For instance, the reasoning process of thought experiments should involve the construal of weighed explanations that happen in two steps: contrast and counterfactuals. The idea of weight is used to determine whether one cause of the phenomenon is more important than another one. Thus, the contrast specifies a situation with which the *explanandum* is compared to mental scenarios, to then drastically reduce the number of possible causes for the following counterfactual reasoning (DE MEY 2006). This apparently is what happened in the case study of this investigation. Statements like the following contribute to the idea that counterfactual thought experiments were indeed used by the scientist as scaffolding to achieve understanding of the phenomenon:

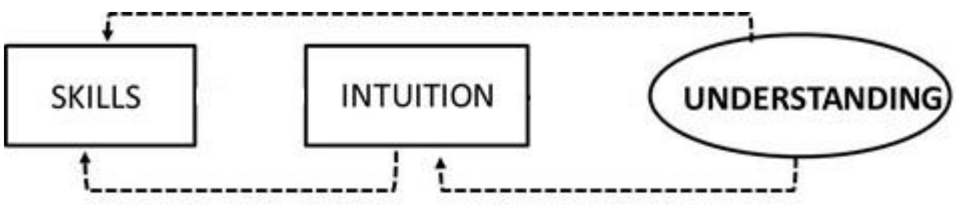
> The heuristics [mechanism sketch] has awakened me to this theoretical gap that existed in me in relation to the phenomenon that I have studied. With each new sketch, new challenges, and solutions, two dimensions of the process of construction of scientific knowledge that led me to lead a process of full immersion in the scientific literature to address the gaps that were gradually perceived. Each new reading enables me to review my sketches (often not materialized, but purely mental), and I will reaffirm my understanding of my phenomenon and the potential contributions that this research can provide [COUTINHO, *personal communication*]

Considering the ability of humans to mentally account for real and imagined situations as well as the predictive power of thought, internal mental models can be structural, behavioral, or functional analogues to real-world phenomena (CRAIK 1943). In this sense, mental models are constructed in the mind to reason with (TAGHARD 2010) and, therefore, can be useful in providing explanations (JOHNSON-LAIRD 1980, 1983), as it is explicit noted in the modeler's statement above.

In addition, the heuristics 'changes in operational components' (Sect. 4.1.9) explicitly intends to suggest adjustments in some elements of the phenomenon scenario in order to predict possible modifications in the system under investigation. The development of external models, represented in Figures XXXI to XXXIV, clearly shows a path from the internal mental models to external models. Although this is in consonance with the idea that successful scientific cognition combines internal representations with external representations, one distinction is important here: internal mental models are not understanding (YLIKOSKI 2009). They rather allow the understanding process to happen, as mediators, which allow one to reach a second level of understanding (Figure XLIII).

Once understanding was achieved, it transforms itself once more in knowledge that will serve as basis for theoretical know-how, skills and intuition (Figure XLIV), supporting in this way the idea of an ephemeral and transient feature of understanding. Thus, a dynamics like this allows the modeler to improve his skills and to further derive increasingly complex counterexamples. But one point is important to highlight, the increasingly improved ability to understand complex phenomenon does not mean that scientific understanding is some sort of cumulative process, an *ad infinitum* addition of information from one level to another. On the contrary, scientific understanding is also a selective and refinement process of information gathered[18]. Remember that intelligibility enables scientists to use theories in order to generate explanations and predictions and being intelligible is a context-dependent feature that is related to the scientist's skill and theoretical virtues (DE REGT & DIEKS 2005). In this sense, scientific understanding is value-laden because it can be grounded on the idea that human developmental processes, such as learning, creating, planning, imagining, building, problem-solving, inventing, etc., can lead to both generative and destructive outcomes (see TATEO 2016). This is reflected in the capability the scientist exhibited in our case study when choosing, say, diagrams, theories, and models that best fit his conceptual framework.

Figure XLIV: Model of understanding - feedbacks



Source: Elaborated by the author.

Looking at this model, some questions are raised: how many levels of understanding are possible? If scientific understanding happens in degrees, is there a higher or greater understanding that can be achieved at a final moment? Do the different standards of intelligibility suggest different standards of scientific understanding?

The existence of degrees of understanding is consonant with the idea of different standards of intelligibility. The existence of degrees of understanding and, therefore, degrees of intelligibility does not mean that in every scientific practice degrees will happen. Considering that scientific practice concerns explanation and model construction, and that the achievement of understanding is content- and context-related, it is possible that the amount of

[18] I appreciate the valuable contributions Dr. Luca Tateo made for this topic.

levels is connected with the *explanandum.* The more complex a phenomenon, the more degrees of understanding and intelligibility may be necessary.

An important difference between understanding and scientific understanding is that the latter is tacitly immersed at a scientific context, where the practices of a scientific community operate. Thus, any level of understanding will be intrinsically related to a given research goal. Therefore, there is no greater or higher understanding, only the understanding that is supposed to be achieved according to *S*'s investigation. Undoubtedly, there will be some kind of increase in complexity, once the understanding in one level becomes know-how and skills for future levels. But this does not preclude the possibility of the (what is called) second level happening before the (what is called) first level. This is only possible when one thinks of this model not as an oversimplified circular or linear event but rather as an account of a waterfall or spiral phenomenon[19] product of a creative thinking process (see BOEHM 1988; EBERT 1994; GUPTA & BHATIA 2012).

5.2 Final considerations

As this chapter intended to expand the discussion on the contextual theory of scientific understanding, it is important to recall the following.

> Scientific understanding is an epistemic and cognitive skill reached when the scientist is capable to develop intelligible explanations (and sometimes derive predictive counterfactual scenarios) about the phenomenon he/she is working (DE REGT 2017:xx).

What this chapter suggests is that the scientific understanding process might happened gradually or not, and these degrees (that might represent different types of understanding) will depend on the goal of the scientist's research. This understanding might enhance the scientist's skills by means of critical self-reflection.

To sum up, the contextual theory of scientific understanding elaborates on a pluralistic perspective on standards of intelligibility that are context- and content-dependent and do not stand for a scientific understanding that occurs according to a specific model. This chapter attempted to show how scientific understanding happened during an ongoing scientific practice. It elaborates mainly on the crucial role of intuition, by means of thought experiment and imagination, as mediator between knowledge and understanding. Even though the process of scientific understanding may be best represented in a spiral thinking model that still needs

[19] I am grateful for Dr. Pinna Marsico's contributions on this topic.

to be further investigated, one important feature of scientific understanding, represented by the model in this chapter, is its ephemeral capability of transformation into knowledge.

PRELIMINARY CONCLUSIONS

Part II of this thesis showed that the contextual theory of scientific understanding can be applied to ongoing scientific practice, not only to historical cases (Sect. 4.1 and 4.2). It also advanced a model of scientific understanding that gives a major importance to the research context of the scientific practice, and the role of the conceptual tools visualizability and visualization in the achievement of scientific understanding (Sect. 5.1).

As the discussions in Chapters 4 and 5 do not cover general practices in science but a very specific case study in ecology, it is only fair to add into this discussion a previous attempt to reconstruct the process of understanding in ecology. Thus, to spice a bit more this discussion I would like to elaborate on the book *Ecological Understanding*, by Pickett, Kolasa & Jones (2007). There are a few reasons to do so: the book is substantially dedicated to the process of explanation and understanding in ecology; it targets the audience of practicing ecologists; it is consistent with the ongoing scientific practice as represented in the case study and also presents similar aspects to those included in the contextual theory of scientific understanding.

It is important to acknowledge beforehand that *Ecological Understanding* is an ode toward an integrative ecology. Throughout the book the term "understanding" is employed in a polysemous way, being related to explanations, comprehension, knowledge, field of research, etc. This gives permission to allocate the authors into the cluster of authors that assumes an explanatory understanding attitude. Even though this hampers a more substantial discussion on a possible distinction between scientific explanation and scientific understanding in ecology, the book is still an impressive attempt to understand how explanations and understanding are achieved in ecology, this still young and heterogenous research field.

Pickett *et al*. (2007) assert that ecology is in urgent urge for integration. Integration as maintained by the authors would be a powerful strategy for advancing basic and applied ecology by effectively bridging existing paradigms, linking levels of organization, and seeking generalizations across disparate themes. On this account, understanding would be a necessary state between reality and theory, establishing relations between what scientists observe and think, being achieved by a process they call "general explanation". In their words, "understanding is an objectively determined, empirical match between some set of confirmable, observable phenomena in the natural world and a conceptual construct".

Understanding, according to Pickett and colleagues, is composed of two pillars: observable phenomena and conceptual constructs. Two other important features are: the domain and the set of tools. An interplay between these pillars is the main method by which understanding develops and change. Accordingly, this interplay must have a clear focus, it must always occur within a specific domain. This domain is the bounded universe in which the dialogue between conceptual constructs and observables is conducted. This is only possible due to a set of tools that enables the scientific dialogue between conceptual constructs and observable phenomena, which are, for these authors, (i) generalization, (ii) causal explanation, and (iii) testing.

Generalization is the construction of patterns by means of three process, *abstraction*, *idealization* and *unification*. *Abstraction* is the identification of the essential features of the phenomenon or interaction of interest. *Idealization* is another type of simplification that deducts influences that might act on the system. Finally, *unifications* extract information from a set of similar observations, usually addressing domains from different phenomena that are difficult to accommodate with one another. It is the generalization across distinct domains that characterizes unification.

Causal explanation makes reference to the interactions, mechanisms, processes and conditions that generate a given pattern or phenomena. In this sense, causes involve a set of contemporary and historical events and circumstances. On the account of this broad scope of causal explanation in ecology, a hierarchical approach can arrange systematically and simplify what could be a network of observations and relations. Stated in this manner, Pickett et al. (2007) acknowledge that in ecology “mechanism” suggests one sort of cause, and this interaction would be nested within the entity or system to be explained. Thus, causal processes and mechanisms can appear at higher and lower hierarchical levels of organization, and can be related to one another in various ways.

Testing, in turn, is the comparison of an expectation (*i.e.*, predictions or forecasts derived from a hypothesis or theory) to observations from the material world

When comparing the ecological understanding theory (PICKETT *et al*. 2007), the contextual theory of scientific understanding (DE REGT 2017) and the scientific practice in the ecological case study in this thesis (Sect. 4.1), it is possible to perceive a couple of intersections among them.

First, the conceptual tools of the contextual theory of scientific understanding (visualizability, visualization, causal reasoning, unification, etc.) indeed help enhance the intelligibility of a theory, while in the ecological understanding theory the set of tools (generalization, causal explanation and testing) exists to relate conceptual constructs with observable phenomena. Although Pickett and colleagues do not make a clear assertion about the set of tools for intelligibility, this connection is possible given statements like the following:

> Understanding here has a specific meaning that we must expose. In a scientific context, the term "understanding" implies that questions about a phenomenon can be answered by referring to certain patterns in nature, relationships among entities and processes, and causes of the patterns and their differences (PICKETT *et al*. 2007:33).

> [..] we believe that one of the surest ways to enhance our understanding in ecology and, consequently, to promote integration of the discipline, is to make the inclusive nature and wide utility of theory in its most general sense better known and comprehended by ecologists (*ibid.* 2007:35).

In other words, understanding is enhanced and, therefore, achieved once a theory is widely applied. A theory can only be used whenever patterns and relationships of entities in nature are recognized, that is, the explanation of ecological phenomena is developed.

Second, these tools (generalization, causal explanation and testing) are perceived in the scientific practice of the modeler in the heuristics application (Chapter 4). For instance, causal explanation is reflected in the heuristics 'operational component distinction' (Sect.4.1.5), 'external regulatory agents' (Sect.4.1.8), 'mechanism sketch' (Sect.4.1.2) and 'mechanism schema' (Sect.4.1.10). Generalization by means of abstraction, idealization and unification is embodied in the heuristics 'mechanisms sketch' (Sect.4.1.2), 'hierarchical structure' (Sect.4.1.3), 'enabling conditions' (Sect.4.1.4) and 'cluster determination' (Sect.4.1.7). Finally, testing can be perceived in the heuristics 'evidence frequency' (Sect.4.1.6) and 'change in operational components' (Sect.4.1.9).

Third, another intersection point concerns the idea of *domain* in the book by Pickett and colleagues. According to these authors, the domain is the set of objects, dynamics and relationships at specified spatial and temporal scales that are the subject of scientific inquiry. The notion of domain helps organize discourse about a specific phenomenon. In the case study, the domain was previously determined by the modeler as being the "main theoretical pillars" underlying the phenomenon (Sect.2.2), being afterwards related to the heuristics 'hierarchical structure' (Sect.4.1.3), 'enabling conditions' (Sect.4.1.4) and 'cluster determination' (Sect.4.1.7). The interesting point is that the domain is taken by the authors to be a crucial element that relates observable phenomena and conceptual constructs, which will be evaluated by a community of scientists at some point. Therefore, it will be subject to revision or replacement in the scientific community, in other words, it is content- and context-dependent.

One last point to claim concern the idea advanced by Pickett *et al*. (2007) that the construction of understanding develops, change and happens in distinct levels. Statements like "understanding puts new knowledge in the context of existing knowledge" (*ibid*. 2007:33), as well as the passage quoted below, are consistent with the model put forward in Chapter Five (figure XLI), stating that understanding happens in degrees and is intrinsically related to the context of research carried out by scientists in an ecological practice (Sect.5.1):

> Understanding may take place at different levels of generality. For example, an ecosystem ecologist may need to know the contribution of individual species or functional groups to nitrogen flux before reaching a satisfying level of understanding. in contrast, and undergraduate student in an ecology course may only need to understand that biota in certain compartments move or transform nitrogen at varying rates depending on their identity and activities, without knowing any of the underlying details (PICKETT *et al*. 2007:35).

The idea of integration in Pickett *et al*. (2007) for the heterogenous ecological science is clearly represented in the case study of model construction examined in this thesis. In several different statements (Sect.4.1 and 4.2) as well as in his final theoretical framework (Part I, Box 1), the modeler addresses unification in ecology in order to make the phenomena successfully explained. Even though the general account the authors give to understanding is related to an integrative assumption, integration must be taken cautiously so as to avoid falling into the idea of a superunderstanding, that is, some sort of complete scientific understanding (see DE REGT 2007).

To sum up, it is acknowledged that Pickett *et al*. (2007) do not make a clear and explicit distinction between knowledge, explanation and understanding which clearly depicts how understanding freeze its meaning throughout the sciences. In this sense, they do not bring a robust process for assessment of understanding. But to give the devil his due, if such distinctions are taken into consideration, they do elaborate on a powerful process of assessment of explanation in ecology. *Ecological Understanding* is a great gain in the ecological sphere in order to deal with the most diverse domains of data and the most diverse theoretical constructs, and depicts a clear path to elaborate strategies for management purposes, such as those reflected in the framework constructed by the modeler in our case study.

CONCLUSIONS

Interdisciplinarity and heuristics as toolboxes for Philosophy of Science in Practice

In the *Symposium on the planning and evaluation of science* (1989), Thomas Nickles brought two examples from the history of science to highlight different consequences scientific discovery might possess for distinct fields. In the first case, David Hilbert made some mathematical achievements in the theory of invariants that ended a research program. In the second case, when Watson & Crick proposed[20] the double helix model of DNA structure, their scientific product fertilized the field for future researches. Nickles uses these examples to debrief how scientists evaluate the fertility of a scientific result, and their confidence that problems are solved. With these points he submits the idea that heuristics appraisal should be much more explored in the scientific field than usually is. Almost 30 years later the publication of his article, *Heuristic appraisal: a proposal*, we still have none outstanding improvement in heuristic appraisal (HA) relating to the development of scientific knowledge.

Recent history of science already showed us that there is an astonishing explosion of "kinds of things" that has become the object of scientific inquiry (DENNETT 2013). One promising way to deal with such breathtaking diversity of data, information, and technology is to defy the standard notions on how science is constructed. Contemporary science already counts on collaborations across sciences, in which several scientists combine individual pieces of knowledge in multi-, inter- and transdisciplinary research to solve complex problems from our society (ANDERSEN 2013). This dynamics is not in total agreement with the standard type of science proposed by Kuhn (1970) and Shapere (1971) of normal and particular disciplines. Their perspectives on scientific innovation fit an agenda consonant to a science that works with an epistemic appraisal, differently than the foregoing supported by Nickles (1989). For decades, interdisciplinary research has been an ongoing topic in scientific debate, but such discussions are shy away to a reevaluation of those perspectives together (HA/EA and specialized disciplines). What is less discussed in the academic circle, thus, is how to combine interdisciplinary and collaborative research with a heuristics appraisal account, challenging standard boundaries of science. For what matters, this thesis was an example of such a query.

This investigation showed how interdisciplinarity and heuristics appraisal not only worked as toolboxes for philosophy of science in practice but also indicated the different positions a philosopher can have in order to study how science is made. This led us back to the issue of how to do a philosophy of science that is not a historical reconstruction, and work with an ongoing scientific process? The question was whether philosophers of science while

[20] Considering the historical account, it is recognized and acknowledged in here the important role Rosalind Francklin had for Watson & Crick model building.

being part of an ongoing interdisciplinary research should perceive their own role as in a lab according to an ethnoscience perspective (LATOUR & WOOLGAR 1979]1986), or as actors according to an action research perspective (TRIPP 2005). Given that PoSiP lacks general protocols and methodologies and that philosophers of science also need to learn how to reflect critically on the standards for evaluating the explanations they are adopting (CRAVER 2007), my defense in here is that it is possible to do both.

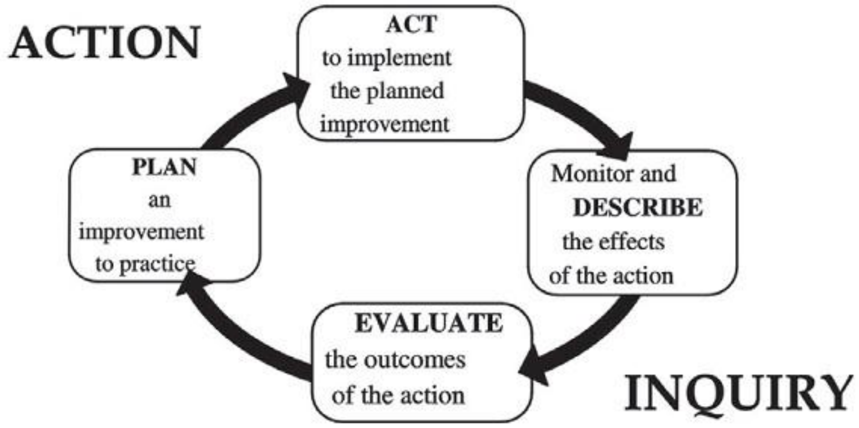
Take for instance Part I of this thesis. Philosophy of science was put into practice (=philosophy of science [in practice]) when scientist and philosopher constructed together the heuristics set. This collaboration attended the demand of developing a new core framework belonging to those fields in order to be interdisciplinary (TRESS, TRESS & FRY 2004). In this sense, the heuristics set represented a product from the combination of the new mechanistic philosophy of science plus ecology. Its construction was an example of how a heuristic appraisal served to cleverly organize a complex body of substantive information, from the elaboration of the heuristics set until the construction of a mechanistic model and further development of an unificationist explanation. Therefore, this collaboration allowed the philosopher not only to observe the scientist but also to participate and make contributions to the heuristics set that the scientist used. Thus, this interaction does not fit into participatory observation often used by sociologists of science because it was not only about going to the scientist's laboratory and observing his practice. On the contrary, there was a clear intention to interact with the scientist and contribute to scientific practice by means of improving the heuristics set with a philosophical background[21]. Such practice reflects one of the purposes of action research, that is, to advance practice by oscillating between taking actions in the field of practice, and inquiring into it – planning, implementing, describing, evaluating and improving changes to one's practice (TRIPP 2005). See, for example, the basic cycle of action inquiry in Figure XLV.

The applications and development of this basic cycle of action inquiry will demand a variation on this same cycle according to the investigation (TRIPP 2005). For instance, in the case study of this thesis we had a "plan" that was to create a heuristics set that would improve the development of model building in ecology. The "action" was to apply the heuristics set and, undoubtedly, develop its framework. The "evaluation" of model building happened by means of analyzing the framework-action symmetry that is provided by the "description" of

[21] I appreciate the contributions of Dr. David Ludwig to these arguments at the qualification trial of this research.

the scientists' practice. This cycle is beneficial for learning more about both the practice and action inquiry of the scientific process and philosophical query all together.

Figure XLV: the 4-phase representation of the basic action inquiry cycle.



Source: Tripp (2005)

In Part II of this thesis, the approach of the investigation was different. The philosopher steps outside from the mutual collaboration to put in practice the philosophy of [science in practice]. In other words, she starts to evaluate the scientist's practices: how did he elaborate an explanation and how did he achieve understanding from the explanation he constructed. It is important to highlight that both paths are reconstructions created by the philosopher, from what and how she judges it happened. These recreations were supported by the interdisciplinary data (interviews, questionnaires, informal communication, etc.) provided from the collaboration that took place in Part I of this thesis. This could fit into an ethnographic study as performed by Latour (1986) and Latour & Woolgar ([1979] 1986), but this investigation is not in entirely accordance with the practices used by these authors for a couple of reasons.

In the case study of this research, the philosopher did not follow the scientist's work in a daily basis to observe and evaluate how the scientist, in his lab, created his explanation and model, because (i) of intrinsic conditions related to both individual Ph.Ds. demands, and because (ii) not all scientific endeavor was restricted to laboratories and machines. In contrast to such technocentric view of science, we must have in mind that not all scientific practice happens inside a laboratory. There are several scientific works that do not require techniques and machineries only disposed in laboratories. A great amount of the scientific inquiry come into being through intellectual effort, and this one can happens anywhere. Several scientists, whenever not in field research (=laboratory), go to the office (=laboratory) to conclude reports, documents, prepare talks, etc. Thus, to follow meticulously the daily laboratory work, in many cases, may go from an anthropologist's work to an ethologist's work, but in either cases we are interested in a philosopher's work. What captivates us most is the content of a scientific report and how-why the researcher came to the concludes he exposes, rather than how he prepares and behaves in an elaboration of a scientific report.

Thus, this thesis manifests a couple of ways in which a philosopher of science can engage with ongoing scientific research instead of a historical reconstruction of scientific practices. First, by collaborating with the practice of a scientist, and second by evaluating ongoing scientific inquiry. It is even possible to defend that a third position could have happened, that is, to evaluate the evolution of this collaborative and interdisciplinary work[22]. Unfortunately, for this case study such analysis was not on demand. Nevertheless, it is asserted that an interdisciplinary research and a heuristics process were fruitful for studies in PoS and PoSiP because they allow philosophy to explore a variety of scenarios, for instance, the construction of scientific explanations and models, the assessment of scientific understanding, and the dialogue between epistemic virtues for the scientist as an epistemic agent (although this last one was little explored in this thesis). All of these also allowed a reflection on philosophy as a discipline that studies science, while constructing its own philosophical knowledge that inevitably is confronted with a historical perspective. Thus, a Philosophy of Science in Practice should stimulate the reflection on its own methodologies, including limitations and prospects for learning from other disciplinarily traditions (ANKENY *et al.* 2011:306). Facing the collaborative and interdisciplinary challenges in this thesis, there are still some open issues for future investigations. I may indicate four, as follows.

First, focusing on practice allows philosophy of science to return to fundamental issues that have increasingly become neglected (ANKENY *et al.* 2011:306). For instance, the assumption that production of knowledge belongs to the *context of discovery* rather the *context of justification*. This puts us in front of the following tensions: past *vs*. present; final product *vs.* ongoing product (science as product *vs*. science as a process); history *vs.* sociology (science as historical constructs *vs.* science as a sociological endeavor). This clearly reflects the fact that PoSiP is advancing but there are still some fundamental questions to be posed, which direct us back to the track of the traditional concerns of mainstream philosophy of

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[22] I appreciate the suggestions of Dr. Hanne Andersen at the qualification trial of this research.

science (SOLER *et al.* 2014). This is claimed in here because of the case study presented in this thesis. This collaborative research aligns with Darden's (2006) idea that "scientific discovery should be viewed as an extended, piecemeal process with hypotheses undergoing iterative refinement. Construction, evaluation, and revision are tightly connected in ways that philosophers of science have often not recognized, even their neglect of reasoning in hypothesis construction and revision". Thus, "instead of viewing science as a series of unconstrained conjectures followed by refutations (POPPER 1968) or as irrational paradigm changes (KUHN 1970), science is viewed as an error-correcting process, with iterative refinement via cycles of construction, evaluation, and revision" (DARDEN 2006:272). This is in complete agreement with the idea of heuristics appraisal defended by Nickles (1989) and applied in this thesis. This grants us the assumption that the interdisciplinarity is still a very successful key:

> Sometimes scientific discoveries occur entirely within one field. In other cases, two or more scientific fields contribute to a scientific discovery […]. Two fields may both seek to discover the same mechanism, investigating different modules of the mechanism using different techniques. Another field may supply items for the construction of an intrafield theory. Two fields may be bridged by an interfield theory. A multifield theory may integrate views of hierarchically nested mechanisms. An abstract mechanism schema from one field may be used analogically to construct a similar type of theory in another field (DARDEN 2006).

I agree with Darden that multifield theory may contribute to scientific discovery, but also to scientific process. Multifield theory demands interdisciplinarity. In this sense the interdisciplinary work will function as a communicative bridge that enables the exchange between diverse zones of knowledge to happen, just like a trading zone[23] (GALISON, 1987). The metaphor of trading zones concerns an arena where scientists from radically different disciplines with distinct practices and languages can trade knowledge in a way that is locally coordinated (GALISON, 1996). These aspects of interdisciplinarity, multifield theory and trading zone leads me to a second issue. It was already highlighted that this new feature of developing knowledge no longer fits the standard notion of science as specialized disciplines. Such critics have already being made for Kuhn, but what about Lakatos' ([1984]1999)

[23] The metaphor of trading zone is also used by Donald McCloskey and goes back to Adam Smith's *Wealth of Nations*: as a society becomes larger and complex, people realize that it is not possible to produce everything that is needed. As a consequence, each person specializes in producing a specific good that will attract a larger number of customers, who will, in exchange, offer other goods that the person needs. Thus, one specializes in order to trade. Differently from Galison, McCloskey does not think that the goods (=knowledge) can be transformed, only redistributed (FULLER, 1996).

research program? How would it be configured the hard core of the program and its protective belt in such interdisciplinary and nowadays science? Would it work?

A third issue is that interdisciplinarity as a social practice is embedded into a larger context than the one provided by disciplinary research. Such socially constructed contexts possess prejudices and vices, one example is institutionalized racism. Prejudice like these may give rise to an illusion of power between researchers which will blur the mutuality needed in a successful collaboration. Thus, philosophers of scientific practice should reflect on how to do an interdisciplinary research absent from misogyny, racism and homophobia. How to practice an interdisciplinarity with a feminist and anti-racist perspective?

A fourth issue to be addressed is the relation of the epistemic virtues, interdisciplinary practices scientific understanding. Once we know that epistemic virtues in science are preached and practiced in order to know the world, not the self (DASTON & GALISON 2010), how the ongoing scientific process may improve the scientist's skills in order for him to become a virtuous agent? Is it possible that to know the self may help improving the knowing of the world? As the *zeitgeist* of the Scientific Revolution was mostly the dissociation of the knower from the knowledge (DASTON & GALISON 2010), is it possible to change the character of science again to foster a rapprochement of knowledge and knower? Would that be prolific?

To conclude, regardless of the position philosophers of science choose to take in order to study scientific inquiry, this exploratory research provided evidence to support the idea that heuristics appraisal and interdisciplinarity can be powerful tools to help philosophers of science assess scientific understanding as well as help scientists construct explanations and models. Considering that no area is totally and completely settled, there will always be new problems and situations to be explored (SUPPES 1978). The large benefit of these tools is that they can be adapted to a galaxy of scientific contexts and deal with a diversity of theories, concepts and methods, reinforcing the idea that a successful field transforms potential generatability into actual generatability of problem solution (NICKLES 1989). Despite their potentiality as a research program be still embryonic, there is no doubt that interdisciplinarity and heuristics appraisal can be great tools to help entangle this Gordian knot that is the methodological approach of philosophy of science in practice.

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