RENÉ WESTRA, KERST BOERSMA, AREND J. WAARLO AND ELWIN SAVELSBERGH

# 28. LEARNING AND TEACHING ABOUT ECOSYSTEMS BASED ON SYSTEMS THINKING AND MODELLING IN AN AUTHENTIC PRACTICE

**Abstract:** This paper is a report on educational design research concerning learning and teaching contemporary ecology. To be able to understand ecosystem behaviour as derived from a complex and dynamic view, learning and teaching systems thinking and modelling skills is essential. To accomplish context-based ecology education, a cultural-historical approach was chosen, using three authentic social practices in which ecology is involved. A sequence of learning and teaching activities was thought out, elaborated and tested in classrooms. Throughout the field test the learning and teaching process was monitored in detail using various data sources.

The results show that the students acquired basic systems thinking; they were able to articulate similarities and differences between the levels of biological organization (individual, population, and ecosystem). In addition, they understood which factors are crucial in an ecosystem and how they work, in particular how they impact quantitatively on each other. Most students were able to explore the required computer models. However, for most of them it remained problematic to build models themselves

**Keywords:** Authentic practices, Complexity, Cultural historical approach, Developmental research, Dynamics, Ecosystem, Modelling, Systems thinking

## 1. INTRODUCTION

Our biological environment can be regarded as a complex adaptive system (Gell-Mann, 1995). Such a system behaves according to three key principles: order is emergent as opposed to predetermined, the system's history is irreversible, and the system's future is often unpredictable. These features result from the interaction of various 'building blocks' and processes at different levels of biological organization (individual, population, and ecosystem) (Holling, 1987). The dynamic behaviour of such a system proves hard to understand for secondary school students studying ecology (Barman et al., 1995; Magntorn & Helldén, 2003; Munson, 1994).

In the traditional approach to ecology teaching, dependencies between populations tend to be represented through 'food webs'. Although this format conveys the idea of a network, it does not contribute to students' insights into the dynamic

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René Westra, Centre for Science and Mathematics Education, P.O. Box 80000, 3508 TA Utrecht, The Netherlands

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interdependencies of populations in the web (Hogan, 2000). Moreover, in many cases the food web representation tends to be transmitted, rather than constructed by the students themselves, which may lead to another misunderstanding: that the food web is a fact of nature, rather than a way of getting hold on the complexity of an ecosystem.

Several solutions have been proposed to prevent these misunderstandings. A recent study (De Ruiter et al., 2005) suggests to replace the metaphor of a *static* structure like the food web by the metaphor of the structures to be built in the game of Jenga (see Figure 1). This could contribute to visualizing the *dynamics* of a complex food web.

Each block in the game could be considered a potential keystone. It is hard to foresee which blocks will be essential for stability in a constantly changing Jenga structure. In a comparable way, the importance of extinct or imported populations for stability of the food web in an ecosystem can vary over time. In such a view, food webs are open and dynamic systems. This new idea could help in the management of ecosystems that are being changed by human influence, although the exact relation between the structure of a food web and the stability of an ecosystem appears to be very complicated (Neutel, 2001).

It has also been claimed that explicit systems thinking and modelling could improve students' understanding of ecosystems (Boersma, 1997; Hogan & Thomas, 2001; Schaefer, 1989; Zaraza, 1995). In systems thinking, an ecosystem is considered to be an open and complex adaptive whole, in which the parts (popula-

Figure 1. In the game of Jenga, each player successively takes away a block and places it on top of the tower, until the structure becomes unstable and crashes

tions or functional groups of populations, and all kinds of abiotic factors) are influencing themselves and each other in nonlinear ways, giving rise to dynamic patterns over time. This kind of thinking may be helpful in directing attention at particular features of the ecosystem like the distinction of hierarchical levels, feedback and temporal delay which cause dynamic, often cyclic but sometimes chaotic patterns.

Students should develop a competence to relate different levels of organization. In addition, students should come to regard each level of organization both as a conceptual unit, which can have properties of its own, and as an assembly of smaller interacting units at a lower level. This could lead to more coherence in their understanding (Verhoeff, 2003).

Concerning the dynamics of a system, computer models, in comparison to the Jenga game, show three advantages. They enable to follow *quantitative* aspects of processes in time, introduce various interacting factors, and study changes on the level of the individual, the population, and the ecosystem.

Research suggests that students learn more about systems behaviour by building or using dynamic (computer) models than by creating static depictions of systems relationships (Kurtz dos Santos & Ogborn, 1994; Louca et al., 2003).

In our view, modelling is an essential part of systems thinking. Ecosystem behaviour is far too complex to be explained and predicted by a single, unified theory. Models draw on a number of theories to help understand a specific problem. They never contain all the features of reality, but only those that are essential to the specific problem. Ecological models facilitate on particular factors, on a specific level of organization, depending on the goals of the model. Such models allow us to encompass our knowledge about the components that interact in a system, the way they interact, and how crucial these interactions are in light of the specific problem (Jørgensen & Bendoricchio, 2001). A model never contains all the features of reality; it only contains those features that are essential in the context of the problem to be solved. An ecological model could be compared to a geographical map, which in fact is a model. Different types of maps serve different purposes, i.e. they focus on different objects. They also differ in scale. In a similar way, an ecological model enables us to focus on particular objects, on a specific level of organization, depending on the goals of the model. For example, in a marine ecosystem the modeller concentrates on cod and its density (population level), because he wants to know what causes the imminent extermination of this species. He does not care about the weight of an individual cod, or about a complete survey of all species of fish in the area under study.

However, both systems thinking and computer modelling are demanding approaches for most students, and it is not self-evident that these approaches can be successfully taught in secondary education. It appears to be a complicated task for students to apply systems thinking to concrete biological instances (Verhoeff, 2003). Moreover, students do not fully distinguish the ideas and/or purposes underlying models, the content of the models, and the experimental data which support or refute the validity or usefulness of models (Grosslight et al., 1991;

Westra et al., 2002). They expect a model to represent the full richness of the real world (Hogan & Thomas, 2001).

Notwithstanding these problems, we stick to introducing systems thinking and modelling in secondary biology education. In our view, these competences are essential to ecological literacy. Perceptions of nature and management of ecosystems are strongly determined by the level of biological organization that a person has in mind. Therefore, seemingly irreconcilable positions in a debate may arise from the participants building their arguments on different levels of organization. In addition, many management measures are based on modelling to predict their impact.

So, our challenge will be to identify ecology-related problems that are simple and transparent enough for students to develop and test their own models, and yet sophisticated enough to 'understand nature', in the sense that students understand what is actually happening when changes in an ecosystem (in a number of cases caused by human intervention) take place.

The central research question in this study is:

How could upper secondary school students acquire an adequate understanding of an ecosystem, emphasizing its complexity and dynamics?

The research question entails the following sub-questions:

- What ecology-related practices seem appropriate for enabling students to grasp and value the role of modelling and systems thinking?
- What pedagogical approach seems helpful in acquiring the skills of modelling and systems thinking?
- How practicable and effective is the resulting learning and teaching strategy?

## 2. METHOD

In our study, a learning and teaching strategy (LT strategy) has been developed by means of a 'developmental research' or 'design research' approach. In developmental research, theory-driven, creative and practicable solutions to learning and teaching problems are designed in iterative consultation with experienced teachers. Researchers and teachers also co-operate in testing the developed LT activities in classroom settings (Lijnse, 1995). To ensure ecological fidelity, mussel breeders, forest rangers, as well as professional ecologists, were consulted in the design process.

The first version of the LT strategy underlying this series of lessons was field-tested in four 5VWO (A-level, 16–17 years old) classes in two different schools in December 2004 and March 2005. The students worked in dyads. A revised strategy will be tested again in 2006.

Throughout the field-test, the learning and teaching process has been monitored in detail, using video and audio recording, classroom observations, notes, sketches, computer models of the students, and interviews with the teachers and students.

Below, we will first present our theoretical framework. Then, we will describe and justify how we proceeded in designing the teaching sequence. Finally, we will report on the field test and come to conclusions.

## 3. THEORETICAL FRAMEWORK

In our view, based on the Vygotskyan cultural-historical approach (Blanck, 1990; Hedegaard, 2001), learning requires a practice that invites students to perform all kinds of activities in a social context. Students work together, talk, discuss, and reflect on their activities. According to this approach the teacher makes a 'double move' (Hedegaard, 2001): he steps down to the actual zone of development of the students, but also challenges them to move to their proximal zone.

Practitioners use knowledge in activities that are relevant in their practice. Not all students have an interest in the field of ecology as such. But every student is a member of society. And ecology matters in society, because man influences ecosystems, and is being influenced by ecosystems. We expect that, by starting from an authentic social practice in which ecology is involved, learning activities could become meaningful for students (Boersma, 2004; Bulte et al., 2004; Kattmann, 1977).

Our cultural-historical approach leads to reinterpreting the use of contexts in science education, i.e. a context is a social practice in which a number of *activities* are carried out to meet specific objectives (Van Oers, 1987; Van Oers, 1998). So, learning will not be meaningful without carrying out activities. These activities are essential to cognitive development in terms of changing students' prior knowledge and skills.

However, to be meaningful, students do not only need a 'broad motive' from the start to act and acquire knowledge and skills they need to answer a central problem. To keep the learning process going, they also need 'local motives' to find answers to partial problems which connect already existing knowledge and skills with the goals that have to be attained during their learning process (Lijnse & Klaassen, 2004).

Since knowledge and skills are often strongly situated, students have to adapt their cognitions when it is required to use them in another non-familiar social practice. This process of adaptation is called re-contextualisation (Van Oers, 1998). In this process students have to infer an abstraction of a concept as it is used in the social practice and to adapt (re-contextualize) it to be useful in the new practice.

## 4. DESIGN OF THE TEACHING SEQUENCE

The first issue was to identify a suitable pedagogical approach to introduce systems thinking and modelling. There have been several attempts to implement a context-concept approach in teaching and learning. It proved hard to tune the chosen contexts with the conceptual requirements of the curricula (Bennett & Holman, 2002). Recently, a new attempt has been made in the Netherlands to develop and implement a context-concept approach in the renewal of upper secondary biology education (Boersma et al., 2005). By relating the context-concept approach to the cultural-historical approach, we might have a solution for the problem mentioned above.

The second issue was to choose as a context a social practice in which ecological key concepts, like complexity and dynamics of an ecosystem and relations between individuals and populations, play an important role in activities. In a densely populated country like the Netherlands, there are many examples of human activities interfering with ecosystems. However, in many cases human control is so dominant that the dynamic behaviour of the system becomes rather predictable even without a model. To the students, such systems would not provide the required need to build a model. By contrast, the context of the mussel culture in an estuarine ecosystem (Easter Scheldt) seems promising because of its economics, the human impact and its manageable complexity from a student's perspective. In comparison to a 'natural' ecosystem, the complexity of the system is reduced by the breeders introducing the mussels as young animals on special locations, in desired quantities, and by the mussels being harvested when they are fully grown, which brings ecological factors like birth rate, density, and death rate under control.

Mussel breeders want to achieve an optimal and sustainable mussel culture. They have requested scientists from NIOO (Netherlands Institute of Ecology) to study ways of optimizing mussel culture in this dynamic ecosystem. In other words, what density of mussels on a bank results in a maximum yield of full-grown animals, without damaging the environment? In the practice of these scientists, working in the so-called MABENE-project funded by the EU, they carry out activities like studying the anatomy and physiology of the mussel, collecting data on biotic and abiotic factors that influence mussels, building apparatus to collect corresponding data, and modelling systems with mussels and their environment (Herman, 2004). So, the practice of the mussel breeders and the practice of the NIOO-scientists do exhibit a certain amount of overlap.

For use in a series of lessons in classrooms both practices have to be separated. In addition, they need an educational transformation, a.o. by identifying the essential activities. For example, to the scientists the relation between their knowledge and skills and the required activities is clear. To the students it is not. They know mussels as organisms, but not their anatomy and physiology, neither how they are part of the population and the ecosystem respectively. But they need to understand how an individual mussel (representing *the* mussel) influences, and is being influenced by his environment, that this individual mussel is part of a population with special emergent characteristics, and that this population is part of the ecosystem, again with emergent characteristics but of a different nature.

For re-contextualisation of the acquired concepts, an authentic practice of nature management (especially rabbits) in a water resource area, the PWN Dune Reserve in Northern Holland has been chosen. The students are confronted with a non-recovering rabbit population in the dune area after a VHS-virus epidemic, in a more complex ecosystem.

For computer modelling Powersim Constructor Lite, a graphic modelling tool, has been used.[1]

The series of lessons concludes with a test. The test items deal with an 'ecological practice' to test the acquired knowledge and skills of the students in context. This is a context of nature conservation dealing with the decision whether or not to shoot elephants in overpopulated areas in Southern Africa. Figure 2 presents the outline of the teaching module. Table 1 describes the sequence of learning activities.

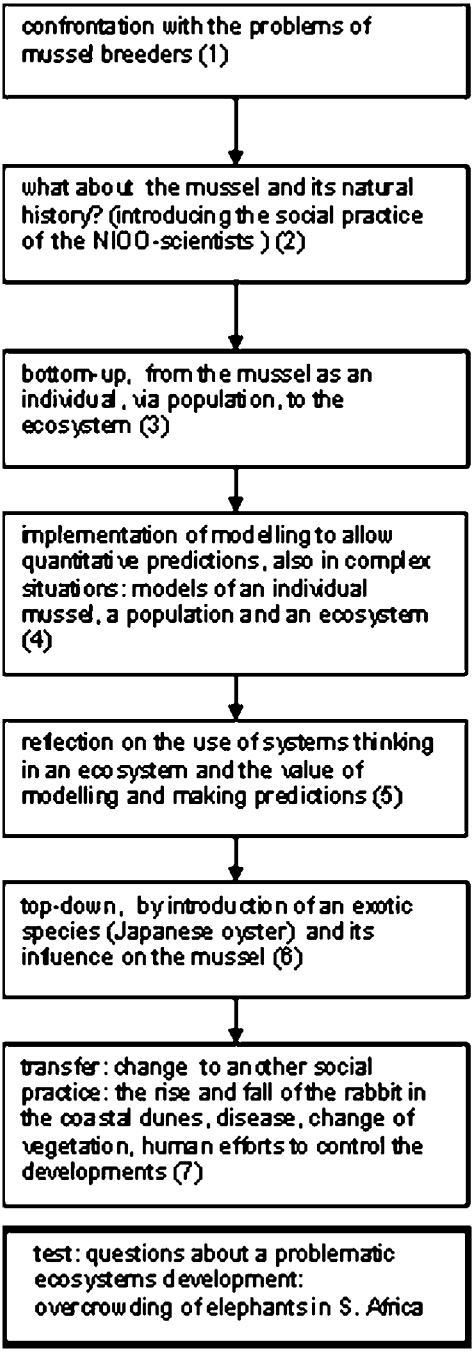


Figure 2. Topics of lessons

TABLE 1. The Sequence of Learning Activities

| Step | Learning activity |
|---|---|
| 1 | Viewing a video |
| 2 | Posing the central problem by means of a group discussion |
| 3 | Investigating mussel anatomy, especially about feeding structure; Determining flesh-weight and dry-weight of a mussel; Depicting models on paper of: an individual mussel and its environment/the population of mussels and its environment/the ecosystem and its environment (bringing in systems thinking) |
| 4 | Modelling with Powersim modelling tool on a computer: a mussel/a population/an ecosystem |
| 5 | Reflection by comparing the models/group discussion |
| 6 | Exploring the effects on the population and on individual mussels of the introduction of a new species in the computer model |
| 7 | Re-contextualising, using acquired knowledge and skills when building a model in another ecology-related practice. |

## 5. FIELD TEST

The collected data from different sources have been inspected and interrelated to find answers to the research questions.

Authentic citations or other results being used are coded with a number, marking the actual lesson (45–50 minutes) out of a series of nine. Besides, a symbol is added (see Table 2) to show the data source. For example, 3C means citations that were recorded in the third lesson.

The students could imagine the problems of the mussel breeders and the dune forest rangers. They also empathized with the role of ecological scientists. However, after the first part of the series of lessons, their enthusiasm declined. Their interest in the mussels was not enduring, and in retrospect, they would have preferred to move on to the rabbits' context earlier. However, when the reasons for the chosen practices and their sequence were explained, they accepted them as a logical choice.

They produced a long list of factors influencing a mussel. Most students were able to depict a simple model including the necessary factors and their interrelations (see Figure 3).

TABLE 2. References to Data Sources

| Data sources | Video- or Audio-recorded citations | Interviews with students or teachers | Modelling activities | Answers on the questions in the final test | Text or drawings on worksheets |
|---|---|---|---|---|---|
| References | C | I | M | T | W |

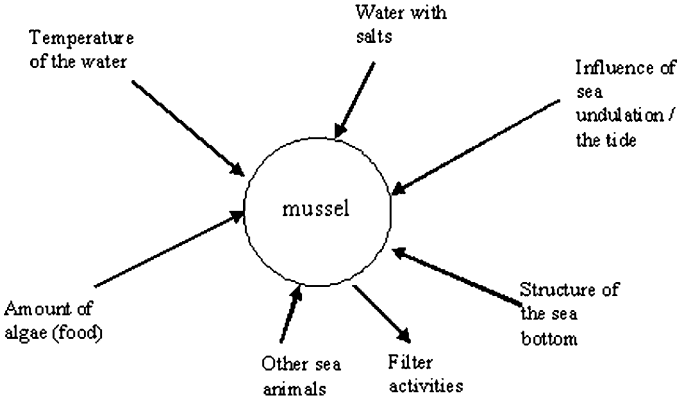


Figure 3. Factors influencing a mussel according to Corinne & Nienke (2W)

*Teacher:* *“What actors did you enter into your scheme with the mussel?”*
*Marjeleine:* *“Sea currents.”*
*T:* *“Do they influence the mussel?”*
*Marjeleine:* *“Yes.”*
*T:* *“What else?”*
*Jessie:* *“A sufficient amount of algae.”*
*T:* *“Anymore?”*
*Edwin:* *“The presence of other marine animals.”*
*T:* *“Why?”*
*Edwin:* *“Well, like crabs and starfish, they eat mussels.”*
*Lisanne:* *“Food, temperature of the water, they cannot live in cold water, I think. Also depth.”*
*T:* *“Why depth, does a mussel need light?”*
*Jop:* *“No, but phytoplankton does.”*
*Edwin:* *“The soil, the currents.”*
*Jop:* *“Currents do influence the soil, I think? And I think salt-content, especially near the coast.”*
*Lisa:* *“The concentration of mussels.” (2C)*

They were well aware of the similarities and differences between the level of organization of the individual, the population, and the ecosystem. For example, they realized that it is not an individual mussel, but the population of mussels that influences the concentration of plankton (food).

*“So, when the density is raised, the mussel competes, and the individual does not grow so well, he is so meagre that he cannot be harvested.” (4W)*

Or that foraging birds like the Common Goldeneye or the Eider Duck exert influence on population level (by decreasing the number of mussels) as well as on individual level (by increasing the weight of the mussels that are not consumed).

They could tell that when birds forage on mussels, this has a negative effect on the density (population level), but a positive effect on dry-weight of the remaining mussels (individual level).

But not everybody agrees on this being positive!

*Fabian*: *"The more mussels are eaten by the birds, the better for the remaining individuals. Their dry weight increases."*

*Josine*: *"Oh, but what is the benefit of that for the eaten ones?" (7C)*

The students were able to build a simple computer model of the growth of an individual mussel based on the daily increase of dry weight of the animal with the help of a worksheet. However, most of them had severe difficulties in formalizing the relations, when they had to build a more complex model themselves. They did not know how to describe the sort of relation between two factors (like multiplication or addition) or how to quantify a relation by using some constant. They had also problems with validating the outcomes of their computer models when a population of mussels was involved and some variables were manipulated (see also Table 3). Many of them were engaged, but got disconnected from the biological reality of the mussels and also lost much of their motivation. When they were invited to explore a complete model, they showed understanding of what was happening and linked their biological knowledge to the model. They discovered that such a complete model could expand their biological understanding. The teachers agreed with this.

*Hamid*: *"I understand a model when it is explained, but I am not able to build it myself."*

*Josine*: *"I work so hard modelling that I tend to lose contact with real world. But after all, I think modelling helps me understanding complex situations in nature."*

*Teacher*: *"I think it a surplus value that complexity and dynamics become clear in these lessons." (I)*

In accordance with the results above, in the final test, most students proved to be able to discriminate between the three levels (individual, population, and

TABLE 3. The Performance of Dyads in Carrying out Various Types of Computer Modelling Activities

| Type of activity | % of dyads, capable of performing activity | |
|---|---|---|
| | School 1 | School 2 |
| Building a model with the help of a work sheet | √ | √ |
| Independently sketching a model | *x* | *x* |
| Introducing the correct relations into a model | *x* | *x* |
| Quantifying relations in a model | *x* | *x* |
| Validating a model, by comparing with real world | √ | *x* |
| Exploring an existing model | √ | √ |
| Extending an existing model | *x* | *x* |

√ more than 50% capable, *x* = less than 50% capable

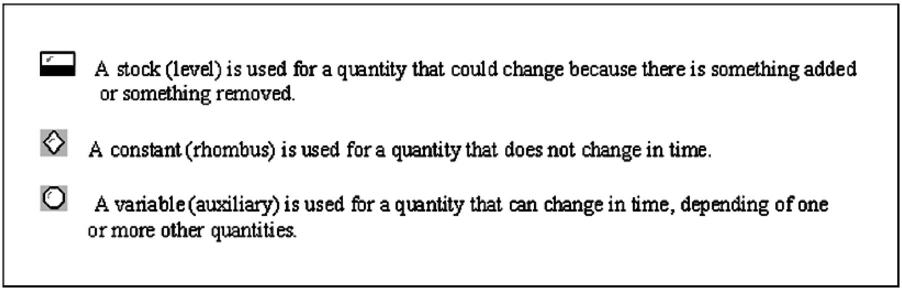
TABLE 4. Percentages of Students' Correct Matches of Scientists and their Level on Focus (T)

| Scientist | Nr 1 (individual) | Nr 2 (ecosystem) | Nr 3 (population) |
|---|---|---|---|
| School 1 (n = 22) | 100 | 48 | 52 |
| School 2 (n = 34) | 95 | 74 | 63 |

ecosystem) in the ecology-related and practice-oriented text about how to deal with overpopulation of elephants (see Table 4).

They were also able to draw models using information from the texts, but most of them did not discriminate well enough between the character (stock, constant or variable, see Figure 4 and Table 5) of the factors that they had used in their Powersim computer models.

A population of elephants is recognized as a stock, but a population of trees is not. That sunshine is a constant factor, not influenced by other factors that have to be used in the model, seems to be understood, but that the factors poaching & hunting and anti-conception, which can be only influenced from outside the model (by human interference) are therefore also constants, seems not be understood.



▬ A stock (level) is used for a quantity that could change because there is something added or something removed.

◇ A constant (rhombus) is used for a quantity that does not change in time.

○ A variable (auxiliary) is used for a quantity that can change in time, depending of one or more other quantities.

Figure 4. The characters of factors used in Powersim models

TABLE 5. Percentages of Students' Correct Matches with the Types of Factor in Powersim

| School | Elephants | | | Trees | | | Poaching & Hunting | | | Anti-Conception | | | Sunshine | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S* | V | C | S* | V | C | S | V | C* | S | V | C* | S | V | C* |
| 1 | 62 | 38 | 0 | 21 | 58 | 21 | 5 | 95 | 0 | 14 | 43 | 43 | 5 | 10 | 86 |
| 2 | 81 | 19 | 0 | 27 | 70 | 3 | 0 | 52 | 48 | 0 | 47 | 53 | 7 | 30 | 63 |

S = stock; V = variable; C = constant, where the ones with * are the correct ones (T)

## 6. CONCLUSIONS

In the former section, the third sub-question has been answered.

As to the first sub question, our choice of the ecological practices turned out to offer good opportunities to introduce systems thinking as well as modeling. The mussel context appeared to be simple enough for students to build initial models, yet complex enough to make the models useful.

The rabbits' context, although far more complex, was also feasible; students were able to apply systems thinking skills acquired in the first context to the second context.

However, embedding ecological problems in a social practice by itself does not necessarily provide sufficient motivation to the students. In addition, the students need to understand why just these practices were selected to deal with the issue. Students' involvement in the issue may fade away at various points during the lessons. These critical moments require explicit attention and reflection in order to keep the students motivated.

As to the second sub-question, we found that students were able to explore models and to derive new biological implications from their models. Students were able to express ideas about effects on individual, population, or ecosystem level. They seemed to be aware of (quantitative) effects from, for example, population level on individual level. However, when it came to designing and implementing their own models, students still experienced severe difficulties in formalizing and quantifying relations, and in evaluating model outcome by applying their biological knowledge. Part of the difficulty may arise from the students being focused at creating a running model; once this goal has been established, the students are satisfied. However, a deeper obstacle may be that the students do not perceive the biological world in terms of numbers; for instance, they do not have any expectation on a plausible range for the dry weight (that is the biomass) of a mussel. It seems to be necessary to: 1. spend time on teaching formalizing and quantifying, for example by group discussion of different solutions and deciding what is the most logical one; 2. stimulate the students to compare their result with 'real world' data'; 3. clarifying the concept of dry weight by let them measure the dry weight of a mussel.

The problems in the correct use of the Powersim symbols for specific factors, found in the test, can be due to problems in understanding the character of a factor and the relation of this factor with others. But another possibility is that the students still have problems with the syntax of the modeling tool.

Further investigations with a revised series of lessons have to be done, with special attention to modeling, to find a teaching and learning strategy which leads to a better development of modeling skills, and in the end to a more distinguished insight into complexity and dynamics of an ecosystem.

## NOTE

[1] This tool is functionally equivalent to the more well-known STELLA-software.

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