Learning and teaching about ecosystems:
systems thinking and modelling in an authentic practice

René Westra[1], Kerst Boersma, , Arend Jan Waarlo, Elwin Savelsbergh
Centre for Science and Mathematics Education, Utrecht University, the Netherlands

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 interdependencies of populations in the web (Hogan, 2000). Moreover, in many cases the food web presentation 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.

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.

[1] Corresponding author. Centre for Science and Mathematics Education, P.O. Box 80000, 3508 TA Utrecht, The Netherlands, R.H.V.Westra@phys.uu.nl, +31-30-2532714

Each block in the game could be considered a keystone in potential. 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 the 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 is 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). Students should develop a competence to relate between 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 1. follow *quantitative* aspects of processes in time, 2. introduce various interacting factors, 3. 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). In our view, modelling is an essential part of systems thinking. Computer modelling enables us to encompass our knowledge about the components that interact in a system, how they are interacting, and how crucial these interactions are in light of the problem under study (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 cods and their density (population level), because he wants to know what causes the imminent extermination of this species. He does not care about the weight of individual cods, 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 conceptual 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 ‘ecosystem’ concept, emphasizing its complexity and dynamics?

The research-question entails the following sub-questions:
- *How could an ecological context be used to experience modelling and systems thinking as meaningful skills aimed at grasping the complexity and dynamics of ecosystems?*
- *What pedagogical approach (learning and teaching strategy) could give the students the possibility to acquire the skills of modelling and systems thinking?*

Method

In our study, a learning and teaching strategy (LT strategy) has been developed by means of a ‘developmental 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 have a thorough ecological background, mussel-breeders, forest-rangers, as well as professional ecologists, were consulted in the design process.
The LT strategy underlying this series of lessons has been field-tested in two classes of 5VWO (A-level, 16-17 years old) in one school in November 2004 and in another in March 2005. 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 recording, classroom observations, notes, sketches, and computer models of the students, and interviews with the teachers and students.

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): she 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 concept 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 meaning when it is required to use them in another non-familiar social practice. This process of adaptation is called recontextualisation (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 (recontextualize) it to be useful in the new practice.

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, see Figure 2 and 3) 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.

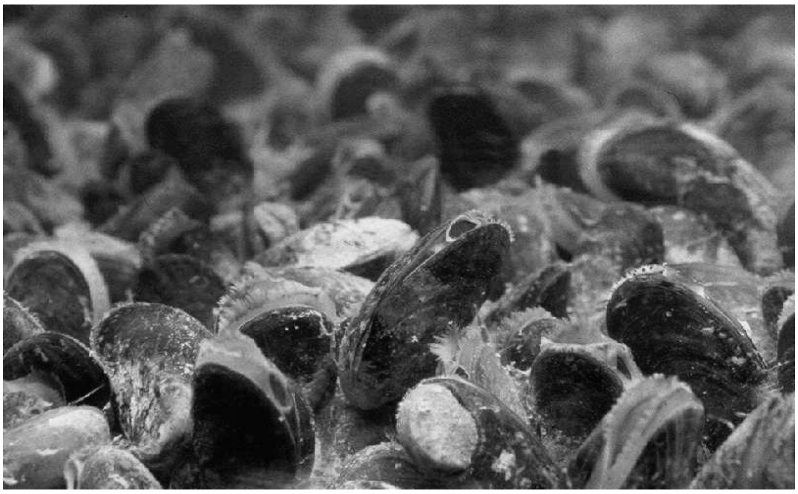

Figure 2: Mussel culture in the Easter Scheldt

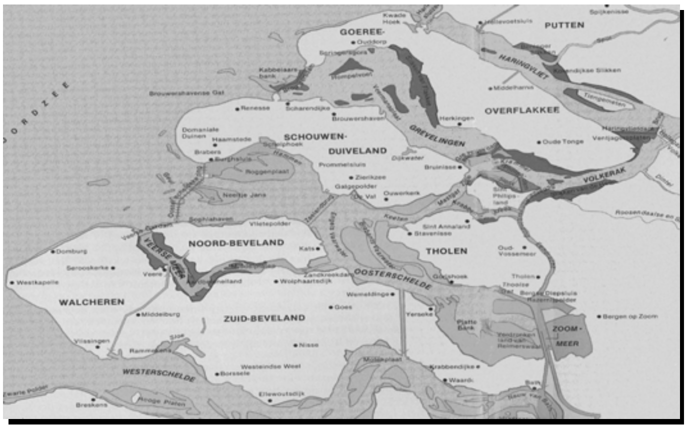

Figure 3: The Easter Scheldt area (in the southern part of the Netherlands)

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: 1. how an individual mussel (representing *the* mussel) influences, and is being influenced by his environment, 2. that this individual mussel is part of a population with special emergent characteristics, and 3. that this population is part of the ecosystem, again with emergent characteristics but of a different nature.

For recontextualisation 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.[2] 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 4 presents the outline of the teaching module and Table 1 describes the sequence of learning activities.

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

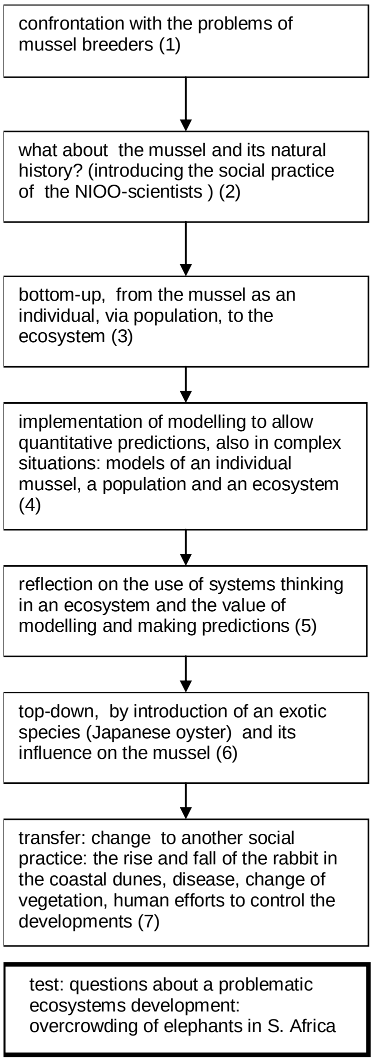

Figure4: Outline of the series of lessons

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	Recontextualising, using acquired knowledge and skills when building a model in another ecology-related practice.

Table 1: A sequence of learning activities

Preliminary results

In the first field-tests, the students worked enthusiastically. They became familiar with the problems of the mussel breeders and the dune forest rangers. They also became acquainted 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. When the reasons for the chosen practices and their order were explained, they accepted them as a logical choice.

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. 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 stimulating the weight of the mussels that are not consumed).

Most students were able to depict a simple model including the necessary factors and their interrelations. They were also 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. But, most of them had severe difficulties in formalizing the relations. They did not know how to describe the sort of relation between two factors (like multiplication or addition) or how to make the relation quantitative 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. They were engaged, but got disconnected from the biological reality of the mussels and also lost much of their motivation. When they were asked 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: *'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.'*

In the final test most students proved to be able to discriminate between the three levels (individual, population, and ecosystem) in ecology-related and practice-oriented texts. 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 5) of the factors that they had learned to use in their Powersim computer models.

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 5: The characters of factors that are used in Powersim models

Preliminary conclusions

As to the first sub-question, our choice of the ecological contexts offers good opportunities to introduce systems thinking as well as modelling. The mussel context provided 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, and students were able to apply systems thinking skills from the first 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. Even when the students' involvement in the issue has been created, there are many points during the lessons where their involvement may fade away. There are various critical steps in the learning and teaching strategy, which require explicit attention and reflection in order to keep the students involved.
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 evaluating model outcome by comparison to 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. invest time to learn them formalizing and quantifying, for example by group discussion of different solutions and deciding what is the most logical of them; 2. stimulate the students to compare their result with 'real world' data'; 3. making a concept of dry weight clear for the students by actually determining the dry weight of a mussel.
Further investigations with a revised series of lessons have to be done, with special attention to modelling, to find a teaching and learning strategy which leads to a better development of modelling skills, and in the end to a more distinguished insight in complexity and dynamics of an ecosystem. As a final aim, the research should yield design guidelines that could be used to implement the teaching and learning strategy with other ecosystems as well.

References

Barman, C., Griffiths, A. K. & Okebukola, P. A. O. (1995). High school students' concepts regarding food chains and food webs: a multinational study. *International Journal of Science Education*, 17, 775-782.

Bennett, J. & Holman, J. (2002). Context-based approaches to the teaching of chemistry: what are they and what are their effects? In O. D. J. J. K. Gilbert, R. Justi, D. F. Treagust & J. H. Van Driel (Ed.), *Chemical education: Towards research-based practice* (pp. 165-184). Dordrecht: Kluwer Academic publishers.

Blanck, G. (1990). Vygotsky: The man and his cause. In L. C. Moll (Ed.) *Vygotsky and education* (pp. 31-58). Cambridge: Cambridge University Press.

Boersma, K. Th. (1997). Systeemdenken en zelfsturing in het biologieonderwijs. Utrecht: University (inaugural lecture).

Boersma, K. Th. (2004). Sleutelbegrippen en handelingspraktijken in biologieonderwijs van 4 tot 18. Paper presented at the ORD 9, Utrecht, 11 june 2004.

Boersma, K. Th., van Graft, M., Harteveld, A., de Hullu, E., van den Oever, L., & van der Zande, P. A. M. (2005). *Basisdocument van de Commissie Vernieuwing Biologieonderwijs over ontwikkeling en invoering van samenhangend biologieonderwijs*. Utrecht: CVBO.

Bulte, A. M. W., Westbroek, H. B., Van Rens, L. & Pilot, A. (2004). Involving students in meaningful chemistry education by adapting authentic practices. In B. Ralle & I. Eilks (Eds.), *Quality in Practice-oriented Research in Science Education* (pp.105-116). Dortmund.

De Ruiter, P. C., Wolters, V., Moore, J. C. & Winemiller, K. O. (2005). Food web ecology: Playing Jenga and beyond. *Science,* 309, 68-70.

Gell-Mann, M. (1995). The Quark and the Jaguar. [Adventures in the Simple and the Complex]. London: Little, Brown and Company.

Grosslight, L., Unger, C., Jay, E. & Smith, C. (1991). Understanding models and their use in science: conceptions of middle and high school students and experts. *Journal of Research in Science Teaching,* 28(9), 799-822.

Hedegaard, M. (2001). Learning and child development. Aarhus: Aarhus Universitetsforlag.

Herman, P. M. J. (2004). *MABENE-veldcampagne in de Oosterschelde*. Accessed at: http://www.nioo.knaw.nl/news/pdf/mabene2004.pdf

Hogan, K. (2000). Assessing students' systems reasoning in ecology. *Journal of Biological Education* 35(1): 22-28.

Hogan, K. & Thomas, D. (2001). Cognitive comparisons of students' systems modeling in Ecology. *Journal of Science Education and Technology* 10(4): 319-345.

Holling, C. S. (1987). Simplifying the complex; the paradigms of ecological function and structure. *European Journal of Operational Research,* 30, 139-146.

Jørgensen, S. E. & Bendoricchio, G. (2001). Fundamentals of ecological modelling. Amsterdam: Elsevier.

Kattmann, U. (1977). Bezugspunkt Mensch [Grundlegung einer humanzentrierten Strukturierung des Biologieunterrichts]. Köln: Aulis Verlag Deubner & Co KG.

Kurtz dos Santos, A. C. & Ogborn, J. (1994). Sixth form students' ability to engage in computational modeling. *Journal of Computer Assisted Learning,* 10, 182-200.

Lijnse, P. L. (1995). 'Developmental research' as a way to an empirically based 'didactical structure' of science. *Science Education,* 79(2), 189-199.

Lijnse, P. L. & Klaassen, C. J. W. M. (2004). Didactical structures as an outcome of research on teaching-learning sequences? *International Journal of Science Education,* 26(5), 537-554.

Magntorn, O. & Helldén, G. (2003). The development of student teachers' understanding of ecosystems during a course-their views. Paper presented at the ESERA, Noordwijkerhout, 19-23 August 2003.

Munson, B. H. (1994). Ecological misconceptions. *Journal of Environmental Education,* 25(4), 30-34.

Neutel, A. M. (2001). Stability of complex food webs [Pyramids of biomass, interaction of strengths and the weight of trophic loops]. Utrecht (dissertation).

Schaefer, G. (1989). Systems thinking in biology education (Vol. 33). Paris : Unesco.

Van Oers, B. (1987). *Activiteit en begrip. Proeve van een handelingspsychologische didactiek.* Amsterdam, VU-uitgeverij (dissertation).

Van Oers, B. (1998). From context to contextualizing. *Learning and Instruction,* 8 (6), 473 – 488.

Van Weelie, D. (2001). Contextualizing biodiversity. In O. de Jong, E. R. Savelsbergh & A. Alblas (Eds.), *Teaching for Scientific Literacy. Context, Competency, and Curriculum* (pp. 99-116). Utrecht: CDß-Press.

Verhoeff, R. P. (2003). Towards systems thinking in cell biology education). Utrecht: CDß-Press (dissertation).

Westra, R. H. V., Savelsbergh, E.R., Kortland, K., Prins, G.T. & Mooldijk, A.H. (2002). Leren door zelf modelleren: constructief en uitdagend onderwijs. *NVOX* 27(7): 331-334.

Zaraza, R. (1995). Systems thinking in the classroom. *Curriculum Technology Quarterly*. Accessed at http://www.ascd.org/publications/ctq/1995fall/zaraza.html