Heuristic principles to teach and learn boundary crossing skills in environmental science education

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Heuristic principles to teach and learn boundary crossing skills in environmental science education

Karen P.J. Fortuin

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1 Introduction

1.1 Background

Since the 1970s environmental degree programs emerged all over the world resulting in a plurality of environmental curricula addressing a wide range of topics and disciplines. The challenges these curricula are facing to educate environmental researchers and professionals have changed over the last 45 years (Camill and Phillips 2011; Proctor et al. 2013). This first chapter introduces the challenges of environmental curriculum and course developers against the backdrop of changes in science and society (Section 1.1.1 – 1.1.3). In order to address these challenges insight in the teaching and learning system is needed and a model that describes this system is introduced (Section 1.1.4). Before the problem statements and research questions are formulated in Section 1.4, the thesis scope (Section 1.2) and the thesis context (Section 1.3) are explicated.

1.1.1 Complex environmental problems and science

Societies are currently confronted with many environmental challenges. Biodiversity is declining rapidly, soil quality is deteriorating, the availability of fresh and clean water is decreasing and climate is changing. Human impact on the Earth system is so big nowadays that it can be considered a global geophysical force. Crutzen (2002) therefore called the current epoch the Anthropocene. Since the discovery of the first hygiene and pollution problems, science has played an important role in putting environmental problems on the political agenda and in designing and implementing solutions (Boersema and Reijnders 2009; Scholz 2011). Natural scientific research has contributed to an improved understanding of the causes and effects of environmental problems, such as soil and water pollution or processes that contribute to climate change. Social science research has contributed to an increased insight in the societal context of these problems and the social and economic drivers and consequences. All this research contributed tremendously to increased insights in managing the environmental consequences of human activities (Kueffer et al. 2012; Reid et al. 2010). Scientific experts traditionally addressed environmental problems by providing knowledge to societal actors. These actors then had to decide what to do with this knowledge (i.e. which interventions to undertake) to alleviate a problematic situation. For problems, such as local noise and water pollution, with unequivocal causes and effects, a well-defined problem definition and straightforward solutions, this approach suffices. Science has thus solved many environmental problems and continues to play an important role in addressing these problems, for instance by detecting new problems, developing new technologies, new business or institutional models or policy frameworks, and by monitoring the consequences. The role of science in dealing with environmental issues has recently changed because of the increased complexity of environmental problems and the rising interest in sustainability (Giller et al. 2008; Ostrom 2009; Reid et al. 2010; Kueffer et al. 2012).

The complexity of environmental problems, such as climate change, biodiversity loss or water shortages, has undeniably increased during the last decades. Complex environmental problems span broad spatial, temporal and organisational scales, are multi-dimensional and involve political controversies. Complex environmental problems are further characterized by many uncertainties, conflicting views on the nature of the problem and the best way to solve them (Giller et al. 2008; Kueffer et al. 2012). Such problems are also called 'wicked' (Balint et al. 2011), but in the remainder of this thesis I will use the term 'complex' problems.

The many uncertainties that are inherent in projecting the future of complex environmental problems, require a more systemic approach (Ostrom 2009). Tackling these problems requires considering interactions that might only emerge and become discernible in the future. For complex problems the traditional approach is less feasible. The interpretation of complex problem and thus of the proposed solutions is often ambiguous. Scientists have become 'honest brokers' (Pielke 2007). They need to collaborate with decision makers or other non-academic stakeholders from civil society and private or public sectors to define research questions together to ensure that these questions are relevant for these decision makers or stakeholders (Kueffer et al. 2012). Moreover, exploring suitable options to address the problem and to design multi-faceted solutions can only be properly achieved by a collaborative approach. The role of scientists in complex problems is rather supporting negotiation processes among stakeholders than providing solutions or plans (Giller et al. 2008).

In addition, the rising interest in sustainability and sustainable development since the 1980s has created new challenges for environmental scientists. Attaining sustainability requires simultaneous efforts to address environmental problems and safeguarding economic welfare and social equity. Complex questions with vast implications arise such as: “What is the best way to reduce greenhouse gasses worldwide?”, “How can we, at the same time, provide sufficient and quality food and water?”, “How to improve human health and human security?”, “How can natural capital be shared in a fair way among all citizens in the world?”, and “What life style, ethics and values are conducive to environmental stewardship and human wellbeing?” and “How might life style, ethics and values support a positive transition to global sustainability?”. Science is unable to provide a clear-cut answer. Science and societies worldwide are facing “grand challenges” (Reid et al. 2010; Mauser et al 2013). Moreover, how to ensure that research results contribute to sustainability is not always obvious, particularly for complex problems that involve many different stakeholders with strongly divergent interests and value systems (Kueffer et al. 2012).

Addressing these complex sustainability challenges requires new ways of collaboration between academic and non-academic stakeholders, beyond the multidisciplinary and interdisciplinary approaches associated with environmental science from the beginning. Innovative transdisciplinary approaches (see Box 1) to produce knowledge and develop and implement sustainable solutions are moving to the centre of investigation (Lang et al. 2012; Rice 2013; Mauser et al. 2013; Kerkhoff 2014). Key arguments for transdisciplinarity are: (i) insights from various academic and non-academic communities of knowledge are needed to ensure that all essential knowledge (e.g., disciplinary, lay, indigenous, or experiential knowledge) is incorporated in research on sustainability issues; (ii) tackling sustainability challenges requires knowledge production beyond problem analysis and scientific understanding of systems. Goals, norms, values and visions need to be included, because they provide guidance for transitions and intervention strategies; and (iii) collaboration between academic and non-academic stakeholders is expected to increase the legitimacy, ownership and accountability for the problem as well as for its possible solutions (Lang et al. 2012).

1.1.2 Multidisciplinary, interdisciplinary and transdisciplinary environmental science education

As a response to the increasing scientific and societal attention to traditional and complex environmental issues, academic environmental science curricula emerged all over the world since the 1970s. Nowadays, universities offer environmental bachelor, master or PhD degree programs in virtually all countries. The importance of training scientists, policymakers and professionals who are able to address the multifaceted environmental issues, is widely acknowledged (Clark et al. 2011; Vincent and Focht 2011; Bursztyn and Drummond 2013).

Environmental science studies the interaction between the biotic and non-biotic environments (or the natural world) and the societal world. Because environmental science focusses on the interaction between natural systems and human systems, it draws knowledge and expertise from a variety of scientific disciplines (Clark et al. 2011; Vincent and Focht 2011). Environmental science is further characterized by its problem or mission orientation. Environmental science research aims to contribute to a clean environment, and to healthy natural and human systems.

Because of these characteristics of environmental science, course and curriculum developers agreed from the onset that a typical environmental degree program combines and synthesizes a variety of scientific disciplines from the natural sciences, the social sciences and the humanities, resulting in multidisciplinary and interdisciplinary courses and curricula (Clark et al. 2011; Vincent and Focht 2011).

In a multidisciplinary study program students are exposed to a variety of disciplinary perspectives through disciplinary courses (see Box 1). Disciplinary knowledge is usually taught separately without making clear connections and without mutual influence between disciplines. The disciplines are taught or offered to the students in an additive way (Feng 2011; Godemann 2006). In interdisciplinary courses learners (or teachers) are stimulated to make connections between various scientific fields and integrate them. Interdisciplinarity entails integrating data, methods, concepts or theories in order to create a comprehensive understanding of a complex issue, question or problem.

Box 1: Various forms of disciplinarity

Multidisciplinarity: involvement of several disciplines, but disciplinary perspectives remain distinct.

Interdisciplinarity: intensive interaction among disciplines resulting in integrating data, methods, tools, concepts and theories, and sometimes creating new methods, concepts or theories.

Transdisciplinarity: integrating academic knowledge from various disciplines with non-academic knowledge. Academic and non-academic stakeholders collaborate and learn from each other.

As explained in Section 1.1.1, not only interdisciplinary approaches (in particular integrating natural science, social science and humanities), but also transdisciplinary approaches (i.e. involving non-academic stakeholders) on various scales are needed to effectively respond to the current challenges and to develop sustainable solutions for complex environmental problems (Lang et al. 2012; Rice 2013; Kerkhoff 2014). Clearly, this has consequences for academic environmental science education.

1.1.3 Challenges of academic environmental science education

Environmental science curricula to date aim to deliver graduates with competencies to study, understand and address complex environmental problems. They aim to deliver graduates who are able to tackle technical, management or policy problems that involve natural resources and environmental quality, who contribute to sustainability, and who are able to collaborate in or lead interdisciplinary and transdisciplinary projects that address these complex issues (Vincent and Focht 2009; Clark et al. 2011b). Environmental course and curricula developers face the challenge to educate these graduates. How to educate such advanced graduates is now an even more relevant question than in the 1970s when the first environmental curricula were established (Clark et al. 2011). Moreover, the question, how to prepare graduates to address complex problems is not only relevant for environmental science curricula but for many other problem oriented educational programs as well (Jacobson and Wilensky 2006).

Environmental course and curricula developers acknowledge the importance of teaching students to critically analyse and synthesize knowledge from various scientific fields, yet there is little scholarship on how to do this (Clark et al. 2011b; Wei et al. 2015). Generally accepted frameworks on educating graduates with the necessary skills to solve complex environmental problems are scarce. The multidisciplinary, interdisciplinary and transdisciplinary teaching and training landscape is very diverse and ad hoc (Camill and Phillips 2011; Proctor et al. 2013). All over the world, examples exist of efforts to adjust curricula in such a way that they meet current challenges (e.g., Vincent and Focht 2011; Clark et al. 2011a; Barth and Michelsen 2013). At Wageningen University the first environmental science program was established in the 1970s. Hundreds of students from all over the world have since then graduated here in environmental science. Building on the experiences at Wageningen University and elsewhere, this PhD explores and develops principles and heuristics (i.e. 'rules of thumb') for the design of environmental science courses and curricula that can meet the current challenges.

1.1.4 The teaching and learning system

In order to address the challenges introduced in the previous section, assessing how students learn and what teachers can do to facilitate this learning, is necessary. Biggs (1999) introduced a very helpful model. He perceived teaching and learning as a system consisting of components that interact with each other in order to 'produce' learning outcomes. His 3P-model of teaching and learning distinguishes the Presage, the Process and the Product stages to describe the interaction between the student, the teacher, the teaching context, the learning activities and the learning outcomes (see Figure 1.1). The Presage involves the student as well as the teaching context that foreshadow the educative process. Student factors include, for example, personal characteristics and the student's knowledge, skills, prior experience and expectations of the learning process. The teaching context encompasses the content to be taught, how this will be taught, the expertise of the teacher, the teaching and assessment methods used, but also the curriculum or the institutional characteristics in which a curriculum or course is embedded. A student influences and is influenced by the teaching context (see Figure 1.1). Students' factors together with the teaching context (from the Presage stage) determine the activities that a student undertakes in the Process stage, namely the learning-related activities. These 'learning activities' in turn lead to learning outcomes in the Product stage. The bold arrows in Figure 1.1 indicate the outcome based approach of this teaching and learning system: the teaching and learning activities are developed or carried out to achieve certain desired learning outcomes. The light arrows in Figure 1.1 illustrate the feedback mechanisms in the teaching and learning system.

Student factors influence interdisciplinary learning outcomes (Spelt et al. 2009), but are in turn also influenced by the learning activities or the teaching context (e.g., through recruitment activities or the curriculum set-up). The broader educational context, such as the organisational setting of an environmental curriculum over different faculties or departments of universities also influences the teaching and learning activities. In fact, the organisational setting is often mentioned as a barrier to interdisciplinary programmes (Clark et al. 2011; Bursztyn and Drummond 2013).

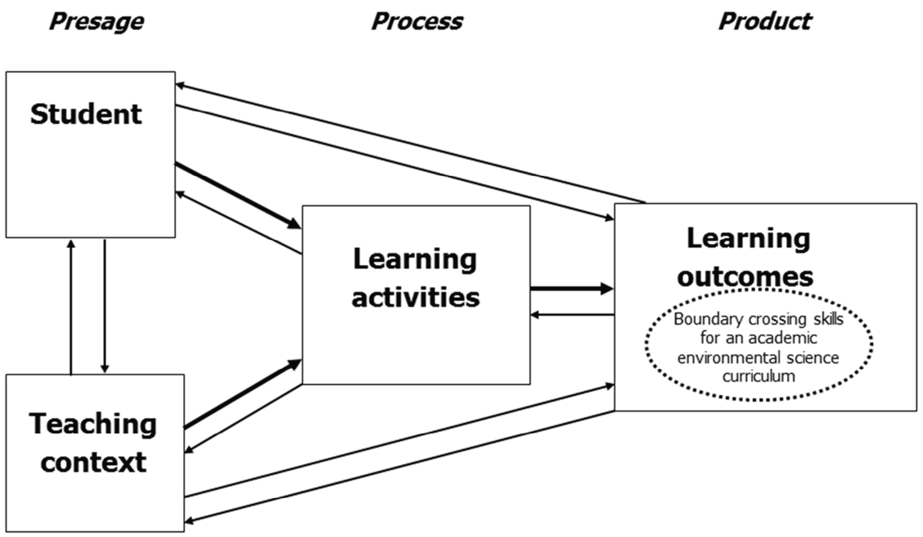

Figure 1.1 The teaching and learning system adapted from Biggs (1999)

The complexity of this system with the various feedback mechanisms clarifies why every class is different. The students are different or the teachers involved are different. But even if the teachers are the same, they are influenced by the students and they might therefore act differently in another student group. Furthermore, the climate or ethos of the larger institutional system and institutional procedures also influence what happens in a classroom (Biggs 1999).

Biggs' (1999) systems approach of teaching and learning clarifies that an educator's role is to create a learning environment that makes a student do the learning activities that will lead to the desired learning outcomes. An educator has to prepare a suitable teaching context. Four elements are crucial here: the curriculum; the teaching method; the assessment procedure; and the climate created in interaction with the students (Biggs 1999, 25).

While acknowledging the interactions illustrated in Figure 1.1, in this thesis I will focus on environmental curricula and courses, while only touching upon assessment procedures. The thesis' scope is further specified in the next section.

1.2 Thesis scope

1.2.1 Introduction

In this PhD thesis, I explore and develop heuristic principles for teaching and learning that enable environmental science students to acquire the necessary skills to address complex environmental problems. While doing so, I will draw on my experience in teaching and learning these skills at Wageningen University (Section 1.3). I will focus on the potential contribution of conceptual models (Section 1.2.3) and of environmental systems analysis (Section 1.2.4). As Biggs' 3P-model (Figure 1.1) clearly illustrates, first the learning outcomes need to be specified (Section 1.2.2).

1.2.2 Learning outcomes

Several attempts have been made to define core learning outcomes for environmental curricula, or in other words, to define what graduates might be expected to know, to do and to understand at the end of their study program (see, for example, for the USA Vincent and Focht 2011; for the UK QAA 2014). This thesis draws on these studies while focussing on the learning outcomes that are characteristic for leading or collaborating in interdisciplinary and transdisciplinary projects. Obviously, domain or subject knowledge or in-depth knowledge about one or more scientific fields is important in addressing an environmental problem and therefore essential for environmental curricula. Discussing detailed disciplinary knowledge requirements is, however, outside the scope of this thesis. This thesis investigates *boundary crossing skills*. Boundary crossing skills are examples of complex cognitive skills. They are 'complex', because they consist of a number of sub-skills, such as the ability to change perspectives and to create meaningful connections across disciplines. The addition 'cognitive' is added to clarify the difference with affective and motor skills (van Merriënboer 1997; Spelt et al. 2009).

Developing sustainable solutions for complex environmental problems requires crossing boundaries. Boundaries are "socially constructed and negotiated borders between science and policy, between disciplines, across nations, and across multiple levels", which "…serve important functions (e.g., protecting science from the biased influence of politics, or helping organize and allocate authority), but … "can also act as barriers to communication, collaboration, and integrated assessment and action" (Cash et al. 2002, 8086). Addressing complex problems requires crossing boundaries both horizontally across disciplines and vertically across experts, policymakers, practitioners and the public (Klein 2004). Graduates of environmental curricula need to be able to cross disciplinary boundaries, cultural boundaries as well as boundaries between theory and practice (Fortuin and Bush 2010). In Chapter 2 the concept of boundary crossing is further elaborated.

Chapters 3, 4 and 5 concentrate on a sub-set of boundary crossing skills (see Figure 1.2). The focus is on the cognitive effort to cross boundaries between disciplines and between theory and practice. Making connections between disciplines, or linking scientific and practical knowledge is a cognitive effort; it requires cognitive skills (Clark et al. 2011). Interdisciplinarity requires knowledge of the disciplines their methods or theories as well as an assessment of these disciplines, methods or theories. It requires the understanding that various disciplinary perspectives exist as well as a critical assessment of these perspectives (Spelt et al. 2009). Higher order cognitive skills are needed to determine which type of knowledge or which method can be or should be used to address a particular environmental problem. Interdisciplinary and transdisciplinary cognitive skills as used in this thesis are examples of higher order cognitive skills that are needed to be able "to integrate knowledge and modes of thinking in two or more disciplines or established areas of expertise to produce a cognitive advancement—such as explaining a phenomenon, solving a problem, or creating a product—in ways that would have been impossible or unlikely through single disciplinary means" (Boix Mansilla and Duraising 2007, p219). Interdisciplinary cognitive skills differ from disciplinary knowledge, such as disciplinary theories, research paradigms or methods including specific technical or analytical skills. Interdisciplinary and transdisciplinary cognitive skills are also different from communication skills, presentation skills, project management skills, writing skills, and other more narrowly defined 'instrumental' skills (Fortuin et al. 2013). The latter skills are very important in interdisciplinary environmental science, but are beyond the scope and analysis of this PhD thesis. In Chapters 3 and 4 interdisciplinary and transdisciplinary cognitive skills are further elaborated.

A crucial component of interdisciplinary and transdisciplinary cognitive skills relevant for environmental sciences, is a student's (or scholar's) ability to reflect on the role of scientific research in solving societal problems (Chapters 3 and 4). It is the ability to reflect not only on the problem and its solutions but also on the process of knowledge production itself. Teaching and learning interdisciplinary and transdisciplinary reflexive skills is addressed in Chapters 3 and 4, but further elaborated in Chapter 5. Reflexive skills in this context refer to assessing the relative contributions of scientific disciplines and non-academic knowledge, and to assessing the role of norms and values in research that aims to address environmental issues.

In summary, in the subsequent chapters first boundary crossing skills, next interdisciplinary and transdisciplinary cognitive skills as a sub-set of boundary crossing skills, and finally reflexive skills as a sub-set of these cognitive skills are operationalised and investigated (Figure 1.2). These chapters also address the teaching and learning activities for these skills.

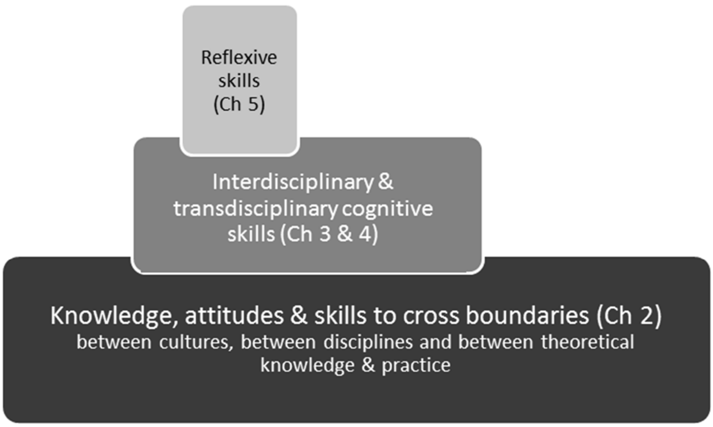

Figure 1.2 Relation between boundary crossing skills, interdisciplinary and transdisciplinary cognitive skills and reflexive skills

1.2.3 Conceptual models

Conceptual models, as meant in this thesis, are abstract representations of reality. They are depicted as two-dimensional diagrams consisting of circles or boxes showing the main elements or variables of a system, and lines or arrows explaining the relationships between these elements. In literature on interdisciplinary environmental research, conceptual models are frequently put forward as a vital tool. They can provide a common framework to analyse and describe complex systems (e.g., social-ecological systems) and to integrate knowledge from different disciplines (Ostrom 2009). They also prominently combine different disciplinary perspectives and terminologies (Leemans 2008) and define a common structure for interdisciplinary research projects. Such a model thus helps to identify the main components of the problem addressed and facilitates the distribution of work among the involved researchers (Olsson and Sjöstedt 2005). Conceptual models are also used as a heuristic tool in a collaborative research project, for example, to assist the knowledge integration and problem framing and to improve communication between scientists with different backgrounds (e.g., Heemskerk et al. 2003).

Several authors have advocated the use of 'unifying' conceptual models to help clarifying the domain of environmental sciences and integrating different types of knowledge in researching environmental problems (Petak 1981, Janssen et al. 1990, Udo de Haes 1991, De Groot 1998, Scholz and Binder 2003, Tapio and Willamo 2008). Given these arguments, conceptual models can likely also be useful for interdisciplinary environmental science education. The contribution of conceptual models to structuring environmental science education is explored in this thesis. Chapter 3 investigates their contribution to designing a curriculum or course that trains students to develop the capacity to analyze and solve complex environmental problems.

1.2.4 Environmental systems analysis

Systems approaches are seen as a way to gain a better understanding of the complexity of the real world. Systems approaches developed since the early 20th century as a reaction to the reductionist approach of most disciplines and the limitations of traditional science to deal with complex real-world problems that require action (Holmes and Wolman 2001; Olsson and Sjöstedt 2004). The strength of a systems approach in dealing with complex problems, is its consideration of the ‘whole’. Such approach thus provides a holistic approach for both scientists and decision makers (Chapter 4).

The literature on definitions and interpretations of systems approaches is rich and covers a wide range of scientific disciplines and applications (see e.g., Olsson 2004; Ison 2008a; Ison 2008b; Jansen 2009). An in-depth discussion of this literature is, however, beyond the scope of this PhD thesis; instead a more pragmatic approach is taken. In this PhD thesis, I investigate what environmental systems analysis as an application of systems approaches to the domain of environmental sciences, contributes to the training of students in boundary crossing skills. As a scientific field, environmental systems analysis aims to develop and apply integrative tools, techniques and methodologies to better understand environmental problems from different perspectives, including natural and social sciences, society, economy and technology, as well as to develop sustainable solutions for these problems (Ahlroth et al. 2011). Because of its characteristics, environmental systems analysis is expected to play an important role in interdisciplinary and transdisciplinary environmental science programmes.

In this PhD thesis, I investigate what education in environmental systems analysis can contribute to training students in interdisciplinary and transdisciplinary higher order cognitive skills (Chapter 4).

1.3 Thesis context

This PhD thesis research is inspired by my teaching experiences at Wageningen University. As a lecturer at its Environmental Systems Analysis group, I have been involved in environmental science education for many years. The four studies that comprise this thesis draw on my experiences with developing and implementing environmental curricula and courses at Wageningen University and teaching courses offered by the Environmental Systems Analysis group. A short explanation of the characteristics of Wageningen University, its environmental science curricula and the education offered by the Environmental Systems Analysis group is therefore presented.

1.3.1 Environmental science curricula at Wageningen University

Wageningen University (www.wageningenur.nl) is a life sciences university (about 4.000 students in 2003; over 10.000 in 2015) situated in The Netherlands. The university's research and education centre around the theme 'healthy food and living environment'. Its mission is 'to explore the potential of nature to improve the quality of life'. Research and education are strongly geared toward practical application. Wageningen University's research and education is characterized by an integrated approach of actual societal themes, such as climate change, (un)healthy lifestyles, the continued pressure on the natural environment and animal welfare. Collaboration between different fields of expertise is common. Wageningen University is a very international university. Researchers are involved in projects around the globe, and the university hosts students from over 100 countries.

The BSc Environmental Sciences offered by Wageningen University is a three year programme that combines natural sciences (including ecology, chemistry and physics), social science (including environmental policy and economics), environmental technology and systems analysis. The contribution from humanities to this programme is limited to ethics and philosophy of science. Within the BSc programme students can select a specific track focussing on either environmental policy and economics, or environmental quality and systems analysis, or environmental technology.

Wageningen University offers two environmental Master of Science (MSc) programs: Environmental Sciences and Urban Environmental Management. These programmes are two years and attract a lot of international students from all over the world. The MSc programmes are thesis oriented and consist of one year of course work followed by a second year of a thesis research and an internship.

Environmental science students learn to "develop analytical tools and models, technologies, or socio-political arrangements, and economic instruments to prevent and control environmental and sustainability issues" (www.wageningenur.nl). This approach is clearly distinguished by Vincent and Focht (2009), who characterized environmental curricula according to the perspective that guides their design. They identified three distinct but not opposing curriculum perspectives: (1) 'the Environmental Scientist', referring to a curriculum that is anchored within a single discipline such as chemistry or biology; (2) 'the

Environmental Citizen', favouring a broad curriculum that includes the natural sciences, social sciences, as well as the humanities; and (3) 'the Environmental Problem Solver', aiming to produce environmental professionals who are able to use systems approaches and draw upon insights and tools from various disciplines in order to address complex environmental issues. The Wageningen environmental curricula are clearly examples of the last category (Fortuin et al. 2011). Particularly in this last type of curricula, students acquiring only relevant combinations of disciplinary knowledge and skills, is insufficient. They additionally need to be able to analyse and design solutions to environmental problems by integrating knowledge from different disciplines (Newing 2010).

1.3.2 Education at the Environmental Systems Analysis group

One of the key chair groups involved in the environmental science programmes at Wageningen University is the Environmental Systems Analysis (ESA) group (www.wageningenur.nl/esa). The research of the ESA group is quantitative and transdisciplinary, and aimed at analysing, interpreting, simulating and communicating complex environmental problems from different perspectives (Leemans 2014). The ESA group combines scientific knowledge from various disciplines, including ecology, economics, technology and policy science to understand causes and effects of environmental problems and the consequences of potential solutions. The mission of the chair group is to develop and improve innovative tools that address environmental change and sustainability. Examples of typical ESA research approaches and tools include (www.wageningenur.nl/esa):

- Appraisal tools for ecosystems, ecosystem services and their valuation;
- Integrated modelling including various components, dimensions and scales (e.g., modelling the causes and impacts of nutrients or waterborne pathogens); and
- Decision support systems for integrated pollution and ecosystem management.

The ESA approaches and tools are applied to advance scientific understanding and support decision making locally, nationally and internationally. The ESA group closely collaborates with other, more disciplinary groups and is involved in international programs, in science-policy assessments and research networks (Leemans 2014).

Education of the ESA group is characterized by training students in multidisciplinarity, interdisciplinarity and transdisciplinarity. This is done in various ways. Some of the ESA courses introduce students to integrative ESA tools, such as scenario analysis, life cycle assessment or integrated modelling. Other courses use a theme, such as the animal production chain, or a real life environmental issue as a vehicle to teach students about various disciplinary perspectives and to train them in combining and integrating these perspectives. In various courses students are stimulated to leave the university campus and to interact with non-academic stakeholders.

1.4 Problem statement, objective and research questions

Environmental science curricula and course developers face the challenge of helping students to acquire boundary crossing skills, essential to develop sustainable solutions for complex environmental problems. In this thesis, I focus on interdisciplinary and transdisciplinary cognitive skills as a sub-set of boundary crossing skills. I draw on my experience at Wageningen University and focus on the potential contribution of conceptual models and environmental systems analysis in teaching and learning these skills. I aim to develop heuristic principles for teaching and learning activities in environmental science that enable a student to develop the necessary boundary crossing skills. The following questions guide this research:

- Q1. What are boundary crossing skills that enhance students' ability to understand complex environmental problems and develop sustainable solutions?
- Q2. What can conceptual models contribute to environmental science education that aims to develop these skills?
- Q3. What can education in environmental systems analysis contribute to developing these skills?
- Q4. What are heuristic principles for teaching and learning activities that aim to develop boundary crossing skills in environmental science education?

1.5 Thesis outline

In order to answer these research questions, I did four studies that are elaborated in the next four chapters. Chapter 2 introduces the *European Workshop in Environmental Science and Management* (EUW), a Master of Science course offered by the ESA group in collaboration with other chair groups at Wageningen University. The didactic model of this course is evaluated and analysed in order to assess whether and how it contributes to developing students' boundary crossing skills. Chapters 3 and 4 operationalize interdisciplinary and transdisciplinary cognitive skills. The contribution of conceptual models (Chapter 3) and environmental systems analysis (Chapter 4) to training students in these skills is explored. Chapter 5 describes an empirical statistical study. In this chapter, first a framework for teaching and learning reflexive skills in transdisciplinary research is introduced. Next, a quasi-experimental setting involving three groups of 30 students participating in the EUW in 2013 is used to assess the framework elements. As is indicated in Figure 1.3 and Table 1.1 below, the four separate chapters (studies) address each one or more of the research questions. The studies are based on literature review, analysis of existing courses and course material, personal experience, and analyses of reflection papers written by students in an authentic learning setting. A more detailed elaboration of the methodology of the four studies can be found in the separate chapters.

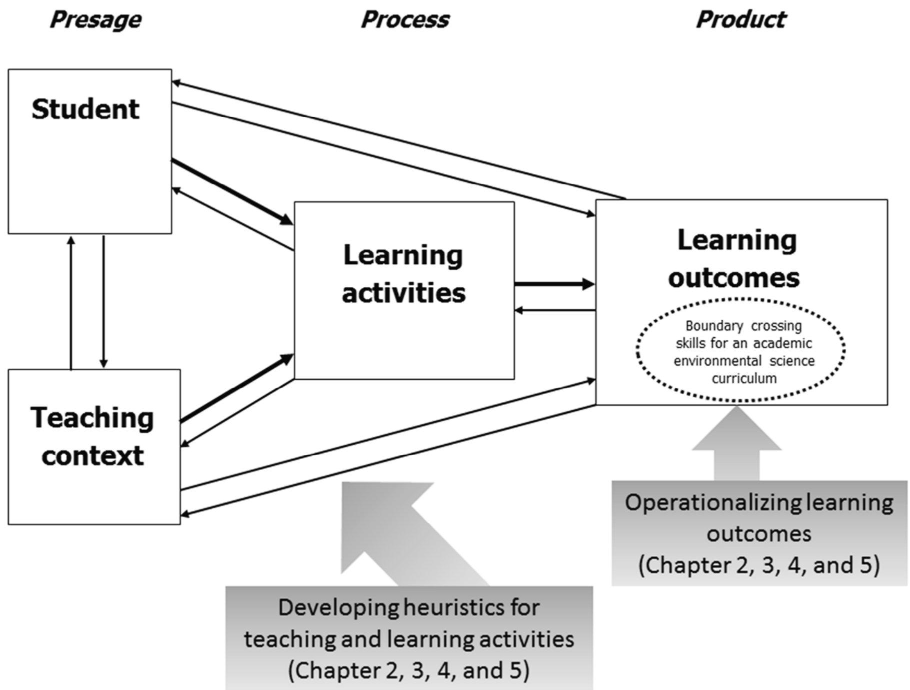

Figure 1.3 Goal and scope of the thesis

Table 1.1 Overview of chapters of this thesis and the research questions addressed

Contribution to:	***Identifying & operationalizing skills (Q1)***	***Heuristic principles for teaching and learning activities (Q4)***	***Research Methodology***
Chapter 2	Boundary crossing skills	Address jointly an authentic environmental problem; matrix approach; field work; teachers as facilitators	Literature study Case study in EUW Student reflection papers
Chapter 3	Problem solving skills Integrative skills Reflexive skills	Contribution of conceptual models to curricula and courses in environmental science (Q2)	Literature study Evaluation of course materials Personal experiences
Chapter 4	Interdisciplinary cognitive skills	Contribution of systems analysis tools, methods and models (Q3) Learning by doing; Learning by reflection	Literature study Case study in a BSc ESA course Student reflection papers
Chapter 5	Interdisciplinary and transdisciplinary reflexive skills	A combination of experience, interaction, theory and reflection	Literature study Pre- and post- test questionnaire in EUW Student reflection papers

2 Educating students to cross boundaries between disciplines and cultures and between theory and practice

Abstract

This paper aims to evaluate and analyse the didactic model of a university course, which concerns an applied academic consultancy project and which focuses on skills related to crossing boundaries between disciplines and cultures, and between theory and practice. These boundary crossing skills are needed to develop sustainable solutions for complex environmental problems. The course is evaluated based on recommendations for successful collaborative interdisciplinary research found in literature. Reflections of two cohorts of thirty students were used to analyse the four components that make up the didactic model of the course: (1) organizational 'matrix structure' in which students work, (2) two week field-trip, (3) customized SharePoint website, and (4) teachers as facilitators rather than providers of information. The paper shows that the course enhanced the students' awareness of disciplinary and cultural boundaries and added to their appreciation of using different disciplinary and cultural perspectives in developing sustainable solutions. Students learned to deal with uncertainty in scientific research and realised that decisions in environmental management are based on partial knowledge. They also learned how to overcome barriers in the design and implementation of interdisciplinary research projects. The paper contributes to the understanding how educational programmes at universities can better equip students to find sustainable solutions.

Based on Fortuin, K.P.J., and S.R. Bush. 2010. Educating students to cross boundaries between disciplines and cultures and between theory and practice. *International Journal of Sustainability in Higher Education* 11 (1): 19-35. doi: http://dx.doi.org/10.1108/14676371011010020.

2.1 Introduction

Environmental scientists are currently facing very complex problems in both the scientific and the professional world. Major questions involve, for example: 'How can society switch from fossil fuels to renewables?', 'How can the decline in biodiversity be halted?', 'How can production chains with minimal waste be developed?' or 'How can innovative sanitation concepts be realized?' To develop sustainable solutions for these complex issues environmental scientists need 'boundary crossing skills' next to domain specific knowledge and communicative and social skills. They need to be able to cross the barriers that exist between theory and practice or between disciplines (Van der Lecq et al. 2006; Spelt et al. 2009). Cash et al. (2002) describe these boundaries as "socially constructed and negotiated borders between science and policy, between disciplines, across nations, and across multiple levels", which they go on to argue "…serve important functions (e.g., protecting science from the biased influence of politics, or helping organize and allocate authority), but… can also act as barriers to communication, collaboration, and integrated assessment and action". Thinking collectively about complex problems requires crossing boundaries both horizontally across disciplines and vertically across experts, policymakers, practitioners and the public (Klein 2004).

How to cross these boundaries is an ongoing debate. Mollinga (2008) argues that *boundary concepts, boundary objects* and *boundary settings are needed.* Cash et al. (2002) stress that boundary work involves simultaneously *salient, credible* and *legitimate* information for multiple audiences. However, to facilitate crossing boundaries, people need to be both interested and capable - something that cannot be taken for granted, as experience in interdisciplinary research projects shows (Jakobsen et al. 2004; Pohl 2005; De Boer 2006; Morse et al. 2007). While there is a body of knowledge illustrating professional needs and experiences in crossing both vertical and horizontal boundaries (Parker et al. 2002; Cash et al. 2003; Klein 2004; Martens 2006), little attention has been given to how to teach those skills. This paper explores how university educational programmes can better equip students to adequately deal with these complex environmental issues and contribute to sustainable development. The main research question therefore is: What educational approaches improve students' boundary crossing skills?

The integration of issues related to sustainability into higher education poses a series of challenges to conventional pedagogy. Steiner and Posch (2006) argue that complex, integrative concepts such as sustainability require a careful balance of interdisciplinarity, transdisciplinarity and self-regulated learning. Students and teachers wishing to focus on sustainability, challenge conventional modes of education and require new methods for integrative learning. Efforts to adjust curricula to meet these challenges are increasingly common (e.g., Scholz and Tietje 2002; Vedeld and Krogh 2005; Steiner and Posch 2006; Morse et al. 2007). These range from programme level to class-based working groups, simulations or case studies. Central to many of these are research-based models, promoting creative, self-regulated learning. While many of them focus on examples taken on small groups outside the classroom environment, there are few that address complex problems through collective learning.

Based on the experiences with the 'European Workshop' (EUW), an interdisciplinary course at Wageningen University, this paper assesses innovative learning approaches and contributes to the dissemination of effective approaches. EUW challenge students to apply knowledge gained in previous courses and think across disciplinary and topical boundaries while working in an intercultural setting. It is scheduled at the end of a first year of course work, before embarking on a second year thesis and internship. The course has run for several years and has evolved into its current focus and structure. This paper reflects on the EUW as a didactic tool. Through this reflection, the authors analyse how the different components of the course contribute to a successful collective interdisciplinary research project and to the individual students' boundary-crossing learning process.

The following section elaborates on the EUW as a didactic model. The course objectives and structure of the EUW are then described, introducing its various stages and key components. Section four evaluates the EUW based first on the authors' reflections of what constitutes successful interdisciplinary research and learning. Second, reflections of two cohorts of students are used to determine what the most important and effective learning processes are of the course. The conclusions will be relevant for both interdisciplinary projects and courses that aim to enhance boundary crossing skills.

2.2 Joint interdisciplinary research as a didactic model

The EUW was introduced a few years ago as part of the MSc programme Environmental Sciences at Wageningen University to provide all students the opportunity to gain experience in transferring theoretical knowledge into practice: a crucial skill for educating environmental scientists. Since dealing with complexity and uncertainty is a central issue of environmental sciences programmes, this was selected as an important additional element as well. As part of the EUW a realistic consultancy project was developed in which students were challenged to work in an interdisciplinary research project to find sustainable solutions for a complex environmental problem.

Another element that made this project even more challenging, was that Wageningen students come from all over the world, bringing into the programme a very rich cultural diversity. Working together on one project enabled the students not only to cross boundaries between theory and practice and between disciplines, but also between their different cultural backgrounds. Combined these three boundaries form the basis of the programme and also the key elements on which the authors based their evaluation. In doing so, a distinction is made between knowledge, attitude and skills (Table 2.1). This distinction allows examining the extent to which students transcend disciplinary knowledge gained in other courses, are aware of different perspectives, and acknowledge the additional value of using these perspectives in formulating solutions to complex environmental problems. Students do not naturally develop an approach to investigate an issue from different angles. This requires explicit attention. A positive attitude or *habitus* towards crossing boundaries is needed (Van der Lecq et al. 2006).

Experiences from interdisciplinary research projects show that educating people to address complex problems proves more difficult according to the number and type of gaps that need to be bridged (Jakobsen et al. 2004; De Boer 2006). Morse et al. (2007) evaluated such projects consisting of a team of PhD students. They identified ‘bridges and barriers’ for interdisciplinary research on three levels: the individual or personal level, the disciplinary level and the programmatic level. They also found that experience with interdisciplinary projects is an important bridge for successful interdisciplinary cooperation (see also Jakobsen et al. 2004).

Table 2.1 Crossing boundaries in the EUW

1. Crossing disciplinary boundaries
    a. Know: being aware of different perspectives
    b. Attitude: see the value of using different disciplinary perspectives
    c. Skill: make use of different perspectives; make use of different disciplines and make connections between them
2. Crossing cultural boundaries
    a. Know: being aware of differences in cultural perspectives
    b. Attitude: see the value of using different cultural perspectives
    c. Skill: being able to collaborate, negotiate and make decisions in an intercultural setting
3. Crossing boundaries between theoretical knowledge and practice
    a. Know: being aware of differences between theory and practice
    b. Attitude: being flexible and open to uncertainty
    c. Skill: being able to deal with complexity and uncertainty

Table 2.2 summarizes the nine recommendations for “exploiting the bridges and overcoming the barriers to conducting interdisciplinary research” formulated by Morse et al. (2007) These recommendations were the starting point for evaluating EUW and used to frame the analysis of the students reflection papers.

Table 2.2 Recommendations for interdisciplinary research (Morse et al. 2007)

1. Establish an accountability strategy
2. Develop formal and informal communication strategies
3. Select team members thoughtfully and strategically
4. Address temporal and spatial scale issues
5. Recognize and respect timing issues
6. Define focal themes and research questions jointly and clearly
7. Emphasis problem definition and team proposal writing
8. Target interdisciplinary training
9. Identify mentors to focus on team integration issues

Interdisciplinary projects are very often team projects. Morse et al. (2007) therefore point out that every team member needs to know his/her role and what he/she can expect from the other team members. This explains the necessity of a clear accountability strategy in which the timeline of required activities and responsibilities of all participants are made explicit. Such an accountability strategy could include specific activities, deadlines of sub-projects and tasks, roles and responsibilities of team members. Morse et al. (2007) also identify communication between participants as crucial in these projects, because team members from various backgrounds use different disciplinary 'languages'. A good and effective communication strategy is thus essential. Communicating transparently can be learned from each other during the project and helps participants to better understand the value of the different contributions. Communication strategies can be either formal or informal. The latter secures an atmosphere that enhances trust and cooperation.

Team members are often selected because of their disciplinary background. However, personal characteristics might be also taken into consideration because they influence how decisions are made under pressure at different stages of the project. It is also increasingly recognised that individuals who are flexible, creative and like to try innovations, flourish in interdisciplinary projects (Jakobsen et al. 2004; Morse et al. 2007). The composition of the research team is therefore a key step in determining the success of the project but also the degree to which members are able to contribute an understanding of the problem and incorporate knowledge from outside their discipline. Anticipating such challenges, Morse et al. (2007) recommend selecting team members, whose visions move beyond disciplinary problem solving skills, whose dedication to see projects through to the end and whose problem-solving skills enable creative thinking.

Disciplinary gaps, which need to be bridged, are rooted in differences between scientific paradigms and scientific languages. Coping with the diversity of temporal and spatial scales or units used in different scientific fields, and conversely, the different time and effort needed to complete specific research tasks is another particular challenge for interdisciplinary projects (Morse et al. 2007). To overcome these barriers requires agreeing on these scales and units of analysis. In many cases, this may require identifying scales that do not conform to traditional units, such as political boundaries, but instead focus on natural units such as watersheds, thereby providing a basis to promote creative, integrative thinking.

A bounded and tangible theme can facilitate integration if it is clear to all participants how this focal theme is related to their own contribution. Team members should, therefore, actively participate to define the problem by writing a comprehensive team proposal (Morse et al. 2007). Discussion of the project goal and research questions among all participants will enhance the commitment of each participant. Formulating data analysis and synthesising conclusions and recommendations together will increase consensus and understanding among the team members about what the project entails (see also Jakobsen et al. 2004). Finally, Morse et al. (2007) focus on the development of training to help participants overcome disciplinary barriers and improve integration in the overall project. They argue that appointing mentors, who facilitate research and the integration process, is an important component of any interdisciplinary project.

2.3 The European Workshop: an interdisciplinary research project

The EUW has evolved over several years to enhance crossing boundary skills through both research and education. This section presents the course structure and the four course components. It also provides a reflection on how successful the course has been in 'exploiting the bridges and overcoming the barriers' to interdisciplinary research outlined above.

2.3.1 Course structure

The EUW hosts a group of thirty students from ten to fifteen different nationalities and disciplinary backgrounds, including social, natural and technical sciences. The main task for the students is to prepare, execute and report on a consultancy assignment dealing with a complex environmental problem for a non-university client on the basis of the academic knowledge and skills acquired during their MSc programme. Given the diverse backgrounds, a central learning goal is to develop the capacity to cooperate and to reflect on the value of different (disciplinary and cultural) perspectives in designing solutions for complex environmental problems.

The students receive specific training in project management and group dynamics. This facilitates the decision making process in the group and the assignment of team member's roles. Although team members were not selected to do the course, as recommended by Morse et al. (2007), they were confronted with assigning themselves challenging roles. This self-assignment is designed to encourage the recognition and further development of personal competencies, which includes the ability to reflect on their own functioning in and contribution to the project in terms of disciplinary knowledge, academic skills, team roles and cultural background.

The course is broken into six phases over eight weeks (Figure 2.1). The time frame of the course is designed to make explicit the temporal 'stages' the students move through, how their roles change in these stages and gain consensus over fixed deadlines. Although meeting these deadlines proves a considerable challenge, it forces students to focus their thoughts and maintain mutual accountability in the work they complete. Students are forced to communicate and act in a succinct manner during the whole project.

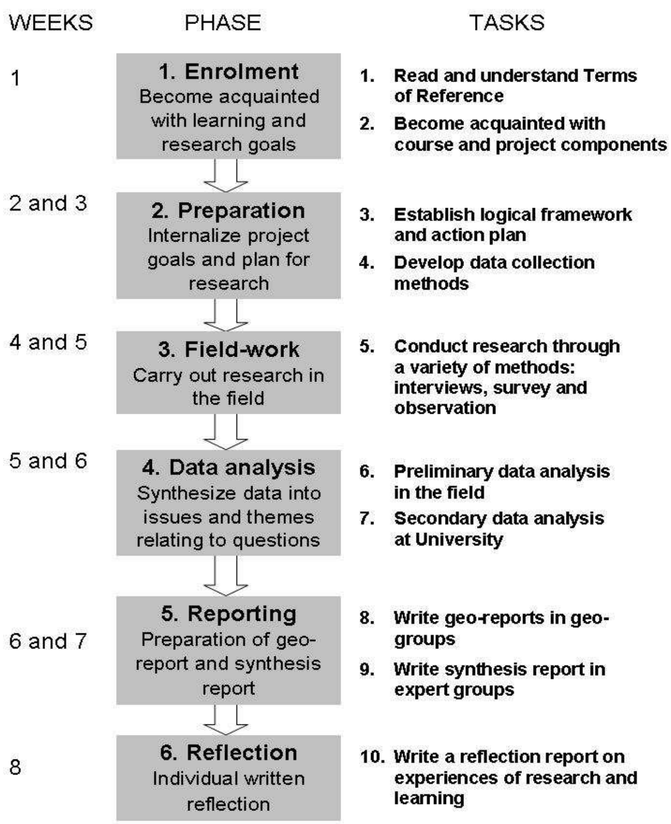

Figure 2.1 Timeline of phases and tasks in the European Workshop

In the first or 'enrolment' phase students are presented with a Terms of Reference (ToR), which guides their work as consultants. Because the ToR is developed with a real client, students are faced with a real world imperative which they are forced to internalize through the joint formulation of the project goal and objectives. The assignment during 2007 and 2008 focused on the planning and management of public and green space in Prague, the capital of the Czech Republic, an issue set within a complex mix of environmental services and a highly politicised arena of spatial planning. In 2007 the students were asked to provide the Ministry of Environment with sufficient information to justify the continuation or modification of an ongoing 'greenbelt' project. In 2008 students were given a similar project by Arnika, a small Czech environmental NGO, who requested information to assist their advocacy work for the improvement of public and green space in the city centre of Prague, and to improve their strategies for raising public awareness. In both cases students were asked to focus on the opinions of key stakeholders and provide specific recommendations to their client for future action.

During the second or 'preparation' phase students have to develop research questions in five 'expert groups' based on pre-defined analyses: policy, stakeholder, ecosystem services and communication strategy. During this phase they are also required to make a logical framework including an action plan and to develop data collection methods. The action plans are prepared in a geo-group, which consists of one member of each expert group, and which is responsible for the analyses in a predefined district of Prague. The action plan makes the responsibilities of each participant explicit and this forms the basis of the third phase: a two week field-trip to collect data on site. In the second phase students are also asked to complete a Belbin team role assessment, making the participants aware of who are their team members what are their strong or weak points and providing them with insights on which they can reflect over the duration of the course.

Students undertake data analysis (phase 4) and reporting (phase 5) in both geo- and expert groups during field work and on return to Wageningen University. In these phases students are challenged most to move between disciplines through meetings and collaborative writing sessions. Students are asked, again under significant time pressure, to synthesize and communicate a range of perspectives into key interdisciplinary or thematic areas.

At two instances students are asked to reflect individually on their learning experience in a written assignment: first, prior to going to the field, when emphasis is on enrolment and preparation, and, second, towards the end of course where they reflect on their full experience. This sixth phase is regarded as a key learning activity as it provides students with the opportunity to reflect on crossing boundaries and competencies that they acquired in the workshop. This reflection includes integrating data from different sources and knowledge from different disciplines, and responding to different perspectives to the problem at hand based on disciplinary and cultural differences.

2.3.2 Course components

To facilitate the students' efforts, a range of components are used that aim to facilitate both research and education: EUW matrix approach, field work in Prague, dedicated website and role of the teachers towards self-regulated learning. These components form the basis of the student reflections and the analysis below.

EUW matrix. A central challenge of the EUW for the students is to work together within a relatively short timespan and to produce one concise consultancy report. To facilitate the communication between all students and to clearly define responsibilities, students are organized within a matrix structure consisting of disciplinary or expert groups and field-work teams or geo-groups (Table 2.3). The matrix means that every field-work team consists of one 'disciplinary' expert corresponding to one of the predefined areas of analysis. Each team also has a Czech speaking person in order to contact local people, to facilitate communication with stakeholders and to assist in presenting the results. A management team consisting of representatives of all groups coordinates the work.

During the whole project, students work in different groups: geo-groups and expert groups to enhance the interconnections between the work. In the preparation phase students start in geo-groups, then formulate research questions and develop data collection methods in expert groups that focus on specific disciplinary analytic tools. In the field geo-groups collect data. Analyzing the data is done in both geo-groups and expert groups. The aim of this matrix is to enable students to work in a disciplinary group and to deepen their knowledge and skills in a specific area of expertise (i.e. the columns of the matrix), but also forces them to cross the boundaries of their discipline (i.e. the rows of the matrix). This enables intensive group interactions and facilitates the process of jointly formulating goal, objectives and research questions as well as team writing. In addition, it aims to clarify the particular role of every individual participant within the larger project.

Table 2.3 EUW matrix approach

		Expert group					
		1. Policy analysis	2. Stakeholder analysis	3. Analysis of cultural ecosystem services *	4. Analysis of provisioning, supporting and regulating ecosystem services*	5. Communica-tion analysis	Manage ment team
Geo group	1	S1.1	S1.2	S1.3	S1.4	S1.5 (CZ)	S1.1
	2	S2.1	S2.2	S2.3	S2.4 (CZ)	S2.5	S2.2
	3	S3.1	S3.2	S3.3 (CZ)	S3.4	S3.5	S3.3
	4	S4.1	S4.2(CZ)	S4.3	S4.4	S4.5	S4.4
	5	S5.1(CZ)	S5.2	S5.3	S5.4	S5.5	S5.5

Note: S – Student; CZ – Czech student acting as translator. * The concept of Ecosystem Services comes from the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2003).

Fieldwork. EUW's central element is the two week field work. Its aim is to provide a setting in which students can deal with the complexity of a range of stakeholders in a real setting. Fieldwork is a mechanism to stress the importance of context, to develop students' ability to integrate classroom-based knowledge and to facilitate communication between participants (Scholz and Tietje 2002; Vedeld and Krogh 2005; Steiner and Posch 2006). During their field work, students are challenged to transcend disciplinary knowledge and to operate on a higher cognitive level by combining and connecting the findings of different analyses and approaches. They are thus forced to communicate on a range of complex managerial and content related issues, but they get also plenty opportunities to communicate informally.

The interchange between geo-groups and expert groups is applied throughout the field work phase. Geo-groups focus on the situation in a city district of Prague, whereas the members of expert groups continue to share and develop ideas on broader temporal and geographic scales. This attention to scale is a particularly important factor in encouraging students to discover the details of rich issues and cases in specific areas (districts) of the city, and then to develop the capacity to position these cases in the broader context of the city as a whole. This challenges students to explicitly address temporal and spatial scale issues.

Communication. To assist formal communication between students and to help them manage a range of tasks associated with the research, a special website using MS SharePoint was developed for the course (Juist and Blom 2008). This website supports the organizational structure of the course and facilitates the formal exchange of information between and within the different groups. The site consists of shared document folders, a calendar and provides a notice-board for announcements. It allows students to communicate and share results and to work collaboratively on writing. Students and teachers also meet in face-to-face group discussions where most decisions are made. Scheduled plenary and feedback sessions with teachers enhance the exchange of information across and between groups.

In addition to formal modes of communication, the course also depends on the informal communication between students throughout the course. The field work period in Prague is particularly important for providing students a new setting in which they depend on each other for a range of course related and personal activities. Here students have the opportunity to discuss, form opinions and informally respond to each other. This time has proven important for fostering creativity and sharing alternative views on disciplines and cultures.

Role of the teachers. The role of the teachers in the EUW differs considerably to traditional lecturing. The teachers stem from different disciplinary backgrounds and provide content related support, but also focus on team facilitation and integration. They are constantly evaluating progress of both geo- and expert groups, iteratively supporting students to take the next step in the research process. Assisting the students to make decisions in a group of thirty people is a key element. The teachers therefore balance the positive and negative influence of individuals, identify leaders and encourage those who are less vocal or active.

As facilitators, the teachers operate differently in the different phases of the course. In the preparation phase, they provide background information on the topic and on the processes in an interdisciplinary project. Although providing content related feedback is relevant also in the next phases, the main focus of the teachers during the field work and data analysis is on facilitating the students' work by asking questions to trigger and enhance critical thinking and alternative views. In the reporting phase, the teachers mainly provide feedback on reporting but also encourage students to look critically at each others documents and learn from it.

2.4 Students' reflection on the course

In this section the EUW is assessed based on the reflection papers of two cohorts of thirty students. In the first year students were asked to describe in general what they learned from the course. In the second year they were explicitly asked to focus on all the course components. Students were asked to reflect on how these components influenced their learning process. Although qualitative in nature, and therefore quite subjective, the authors think the results are instructive.

2.4.1 Matrix approach

The enthusiasm about the matrix approach developed over the duration of the course as the complexity of the problem increased and the students discovered that a clear structuring component was necessary. Students argue that a major advantage of the matrix was its role in forcing transparency and accountability between team members. As one student put it, "the matrix was a watchdog". The matrix emerged as a key problem-solving tool as conflicts arose, deadlines drew near, and team work and efficiency was needed. As one student commented, "It is an optimal way to organize thirty students that have different cultural and disciplinary background in one project team". In a similar vein another student noted that it improved the coherence of the research, by ensuring: "…that participants had a common focus and that data analysis would be done in a similar way".

Many students also value the matrix approach because it enhanced their learning by forcing them to constantly switch between groups and argue their position on a problem in different settings and against different disciplinary knowledge and cultural backgrounds. As one student remarked, "More contacts with more people enriched me personally by forcing me to communicate with students with different personalities… I could observe and compare various points of view." Similarly another student stated "diversity is useful and helpful because I was able to learn many things from others." This diversity is a key achievement of the matrix approach, which also fosters multiple perspectives by forcing students to be analytical and creative in defending or justifying their position, either in disciplinary (expert) or interdisciplinary (geo) groups.

Some students explicitly noted the benefits the matrix brings when moving between their two groups. At the start of the project critical students argued that the matrix having a pre-defined set of disciplines, was too limiting. However, faced with the increasing organizational complexity towards the end, the matrix comprehensively structured the iterations to improve the reporting and helped the communication between expert and geo-groups. It also provided them with a starting point for developing their disciplinary knowledge before branching out to other disciplines. As one student clearly states, "…having a thorough knowledge on one specific topic is much better than just having general knowledge about all the topics involved". However, others recognized some barriers emerging as they moved between their two groups. One student argued that she felt personally more attached to her expert group than her geo-group because her views and comments were "not welcome in some others expertise areas… according to them it was not my area". Such conflicts seem an essential part of the interdisciplinary learning process.

The matrix was also noted as a useful tool in overcoming cultural differences and boundaries, and was reported as enhancing the learning experience of all the students. One student explicitly argued "The matrix structure allowed the intercultural exchange of ideas" – something that was an explicit goal of having multicultural geo-groups. She goes on to explain, "It showed me that an idea that I have, is not right or wrong, but that it is possible to combine different ideas and adapt them to the process". For her, and most other students, the matrix structure forced them into open exchanges where both disciplinary and cultural exchange provided new insights that otherwise may not have emerged.

Despite the many positive points on the matrix structure, several criticisms also surfaced. Some students, for example, criticized the rigidity of the matrix approach, defining expert and geo groups *a priori.* This limited their ability to bring forward new ideas and approaches. A few of the students argued that this limited their creativity and was de-motivating. When issues that didn't completely fit within the matrix structure, were identified (e.g., using new data collection methods or statistical analysis that were relevant to all groups) some got confused.

The complex nature of the matrix was also seen by some of the students as leading to an "excess of democracy" - referring to a degree of fatigue from managing and communicating within their simultaneous roles. One student explained how her opinion of the matrix changed over the duration of the course: "…at the beginning of this workshop I could see a big advantage in the presence of so many diverse opinions in our team". This opinion changed towards the end of the course, "…what was advantage at the start… suddenly turned into disadvantage at the end… [because] different opinions obstructed our work [when] we were facing deadlines".

The project's management team (Table 2.3) should consist of students with relatively more experience and reflect the cultural diversity of the students. In 2008 the management team was dominated by Dutch students with little management experience. Their consensus management style was considered problematic by some of the other students. One student explicitly put this down to cultural differences in management styles, stating "…in my culture, I am not used to be consulted but pointed to do things". She recognized that the voluntary basis of work sharing was inherent in the management style of this management team, this also led to confusing and time consuming situations, which she considered unconstructive. In 2007, such problems did not occur, probably because the management team was more diverse. Despite the rather complex nature of the matrix structure, it was generally well received by students and most of them saw the matrix as an adequate organizational tool.

2.4.2 Field work

Being abroad for two weeks together in the field was considered as the most valuable component of the course. In this period students were clearly confronted with the differences between theory and practice, and experienced the importance of good planning, management and effective communication skills. For most of the students, it was their first experience in doing a real research project and that helped them to appreciate the benefits and challenges of carrying out empirical social and environmental science. As one student pointed out, this gave her the feeling that she was under pressure to find something 'new', which she had never had doing classroom based education. However, the complexity of reality and the differences and incompatibilities in the information they received from different respondents proved confusing for most of them. The field work made many students realize the importance of a proper preparation period and the value of project management tool, but also the flexibility needed in using these tools in order to overcome unexpected circumstances.

When reflecting on the field work many students indicated that they learned a lot from applying different data collection methods. As one of them wrote: “The different methods of data collection in the field were known by me only in theory”. Another student noted: “The fact that I was involved in the observations and the interviews was a good opportunity for me to apply these methods and see the difference between theory and practice”. Nearly all students stressed how deciding on criteria for interviews or observation schedules forced them to develop communication and negotiating skills. The plenary discussions also showed that methodological decisions were extremely important in the research process. Some of these decisions proved problematic. This surprised students. Indeed, the fact that consensus was rarely achieved over such decisions (even late into the field work period) emphasized the contested nature of interdisciplinary – and indeed intercultural – research. Overcoming this remained a challenge for many of the students.

This intensive period of living and working in a foreign country sometimes resulted in miscommunication and conflicts. In general, however, students consider it “an excellent teambuilding exercise”. Many stress that the field period created opportunities for discussions, reflection and amazement on the available diversity of customs, approaches and expertise. They considered this an enriching experience. As one student emphasized:

> The cultural variety of the group was part of this wonderful experience. To share not only knowledge and practice but also personal life with people from so many countries was amazing. The cultural interchange, the debate, the confronting and parallel opinions increased the overall quality. Furthermore, sharing with them a novel experience of travelling to another country with another language is certainly among the things I will never forget from this project.

For the Czech students, who had additional responsibilities for translations and group logistics, the resulting close contact with such a variety of foreign students also strongly enhanced their learning experience. One comment made by nearly all these students was their surprise at how insightful ‘outsiders’ could be, even in a topic that was new for many. One of these students was struck by the frankness of these opinions, which are usually not voiced. She explained: "...students that do not come from my country are less bounded by cultural and social patterns and stereotypes. For example, they were openly talking about corruption. This amazed me!" Indeed, this openness was seen by many as culturally determined. However, other barriers were not overcome. An Asian student noted, for example, that negotiating different approaches to data analysis between students of different nationalities was sometimes a challenge because the eagerness of European and African students to argue approaches and the inexperience to do this by Asian students.

Learning from the research experience and dealing with cross-cultural communication are explicit aims of the course. The EUW is designed in such a way to benefit students of diverse backgrounds. However, one unexpected benefit was the particular impact it had on Dutch students. One of whom remarked that she was extremely surprised and happy that she was finally one of the 'international' students by not being a 'local specialist'. This is interesting in the context of the programme at Wageningen University where, despite an active and successful programme of internationalisation, there sometimes remain prejudices against the skills and capacity of international students by Dutch students. Exposing these students to experience the difficulties of working abroad is therefore regarded an additional benefit.

2.4.3 Website SharePoint

The website developed using MS-SharePoint was an essential component of the course that students used to share information. All students agreed that the site facilitated communication and coordination between group members, between different groups and between students and teachers. They consider it a very useful tool to exchange announcements, to store (draft) documents and to confirm appointments. SharePoint was considered particularly important when faced with the difficulty of writing a coherent report with thirty authors. As one student stated:

> SharePoint proved to be really fundamental during the last phases when we analyzed the data and wrote the reports. Many people were working on different parts of the same report, but everything was available on-line and all participants were enabled to follow the work in progress.

Despite the positive experience with SharePoint, it required a very different approach to communication than students were used to. They recognized that SharePoint forced them into a much more active role. This, they noted, was enhanced by the mutual activity and by having access to all updates of draft documents. Students were therefore forced to continuously check and recheck their progress. Forcing students to engage with the information in a single location was seen positively, but apparently required a mode of collaboration and communication that had not been taught before in other courses.

SharePoint was also indispensable to support creativity and providing a tangible structure during the research. The ability to add, amend and design various elements of the group sites (both for geo- and expert-groups) was highly appreciated by the students. In line with the learning goals, students enjoyed the ability to diverge from a rigid structure of teaching and information transfer to organize, present and communicate information as they wished. One student stated "…although SharePoint had a backbone, it offered at the same time space for every group to arrange its own site… and keep it according to their own preference". Creativity was paralleled by comments about the SharePoint's clear structure, securing students when the problems and discussions in the project became complex. According to few students SharePoint assisted by mirroring the matrix and balancing the complexity of the problem with a tangible structure. In the words of one student, if the problem or discussion became to difficult, they could always return to SharePoint to (re)build their comprehension.

2.4.4 The role of the teachers

Most of the students openly recognized the facilitation role played by the teachers. Many of the students appreciated the teachers' stimulation to think critically by asking questions and providing tools rather than telling them exactly what to do. They acknowledged that this approach enhanced their learning process. As one student pointed out: "If we were 'spoon-fed' by teachers, accomplishing the project would have been easier but we would not have learned as much". Echoing this sentiment, another student wrote: "The teachers never told us: You should do this and that! We always had to find our own way".

Many of the students described that they realized after some weeks that the teachers acted as coaches, who stimulated the research process more than the results. However, it was unnerving for most students to learn that teachers also could not provide the ultimate answer to a problem. This was in fact best illustrated in the 2007 course, where a student asked whether they could obtain the best 'answer' to the project when the course was completed. Overcoming this insecurity was difficult for both students and teachers alike. Revealing this apparent uneasiness associated with problem-solving-in-practice was for some students a major revelation, discovering, as one student put it, that: "…justification is a very significant element in the [research] process… It can validate your choices or it can reveal the need to reconsider". The same student noted that the most valuable lesson she learned was that: "there is no 'secret recipe' that you have to discover in order to solve any kind of problem you are appointed to. It is only a matter of choices that you make, from the very beginning". This emphasizes an important lesson of the course: understanding the uncertainty associated with scientific and especially interdisciplinary research. The structure and components of the course addressed this uncertainty explicitly.

There was also a fine line between the teachers providing feedback that challenged students and feedback that overwhelmed students. A student, who was a member of the management team, commented particularly on this point. She argued that during the evening plenary sessions in Prague the students got the feeling they had "not done enough, thought enough and tried enough to get the best out of their project". She continued to argue that the teachers should consider the impact on students' confidence of constantly challenging students to think beyond their own disciplines and beyond the immediate scope of the task at hand. This pressure could actually undermine a student's confidence. Although this comment was raised only once, it does indicate that teachers should be aware of the students' limits in such a complex interdisciplinary research project.

Other students were also frustrated by the teacher's continual query of "What do you think?" in response to practical and conceptual questions. Under the actual time pressure and faced with what was perceived as an "excess of democracy" (indicating fatigue from discussion), students noted they felt they were making decisions rather arbitrarily and would have liked more solid advice from the teachers. For many students this facilitation rather than lecturing was a new experience from what they were used to. Some students felt confused and insecure about what the teachers expected from them and whether their progress was adequate. Others commented on the endless, sometimes very frustrating group discussions not leading to any decisions. Overall it appears that the students would have liked the teachers to take up more leadership and provide the proper arguments to make difficult decisions. For example, one student, although highly appreciating this form of teaching, argued that: "…sometimes we would welcome more concrete information because we were facing deadlines and this method is time consuming".

The insecurities voiced over the decision making process and the time pressures were partly intentional to provide a platform, which stimulated different personalities to show leadership, which allowed for making and correcting mistakes, and which facilitated the emergence of the necessary creativity in problem-solving. It also resulted in a different relationship between students and teachers: one in which expert knowledge was replaced with sharing experiences and open discussion. This was new for all students and at times difficult to accept for them. Those students who realized the different role of the teachers early in project were able to get more out of the course. As one satisfied student described, she and her group were "…free to have imaginations and practice them. Then, learn from our own mistakes".

2.5 Conclusions

In this paper the EUW was presented as a didactic model in which students work on a realistic consultancy project through a well structured, collaborative interdisciplinary research project in an intercultural setting. Based on the evaluation of the course and students' reflections, the authors conclude that the EUW was very successful as a didactic model to train students' boundary crossing skills. This model showed students how barriers can be overcome and also how participation in such a well structured project contributes to enhancing their boundary crossing skills. Applying established recommendations for successful interdisciplinary projects proved to be essential in developing the didactic model of the EUW.

Two components of the EUW, the matrix approach and the field work, particularly contributed to enhancing students' awareness of disciplinary and cultural boundaries. They also added to the students' appreciation of using different disciplinary and cultural perspectives in solving problems. The students developed a positive attitude or *habitus* to crossing boundaries, a precondition for being able to cross them. Based on the student reflections, however, it is not possible to quantify the improvement of these boundary crossing skills.

This paper illustrated that collaborating in a diverse group of people intensively over a short period is a challenging and partly unpredictable exercise, but offers the opportunity to challenge and learn from each other. However, this requires careful planning and facilitation. Few aspects of the course therefore require further consideration and development. One is the teachers' balance between providing a challenging environment, encouraging the students to take decisions and responsibility for their work, while on the other hand ensuring that 'democratic' fatigue does not set in. Furthermore, teachers should deal with the thin line between encouraging students to creatively explore their data while minimizing the risk of undermining their confidence. Another aspect concerns the rigidity of the matrix approach. Innovative ways to deal with this rigidity are needed. For instance, what to do with research skills, activities or approaches that don't fit directly in the matrix? And, how applicable is the matrix approach to other areas of interdisciplinary research? This is of particular concern as the EUW approach will be expanded as planned in 2009 to a coastal and marine management workshop in the Crimean region and an urban topic including the field of technology.

By working on a real project in an intercultural setting students were confronted with shortcomings of scientific research and the often politicised nature of environmental management. Learning to cope with these issues by questioning the reliability of information and realising that decisions are often made in a particular context, exposed the students to the central challenges of crossing boundaries between theory and practice, disciplines and cultures. This realisation will be transferred into research and professional skills as they advance with their academic and professional careers and will be further exposed to the complexity of environmental and societal problems. Realising that one should cross boundaries to solve problems could be one of the most important elements in their education.

3 The value of conceptual models in coping with complexity and interdisciplinarity in environmental sciences education

Abstract

Conceptual models are useful for facing the challenges of environmental sciences curriculum and course developers, and students. These challenges are inherent to the interdisciplinary and problem-oriented character of environmental sciences curricula. In this article, we review the merits of conceptual models in facing these challenges. These models are valuable because they can be used to (i) improve the coherence and focus of an environmental sciences curriculum, (ii) analyse environmental issues and integrate knowledge, (iii) examine and guide the process of environmental research and problem solving, and (iv) examine and guide the integration of knowledge in the environmental-research and problem-solving processes. We advocate the use of various conceptual models in environmental sciences education. By applying and reflecting on these models, students start to recognize the complexity of human-environment systems, to appreciate the various approaches to framing environmental problems, and to comprehend the role of science in dealing with these problems.

Based on Fortuin, K.P.J., C.S.A. van Koppen, and R. Leemans. 2011. The Value of Conceptual Models in Coping with Complexity and Interdisciplinarity in Environmental Sciences Education. *BioScience* 61 (10): 802-14. doi: http://dx.doi.org/10.1525/bio.2011.61.10.10.

3.1 Introduction

Since its emergence in the 1970s as a new interdisciplinary research and education field, the environmental sciences have acquired an established place in academia worldwide. In virtually all countries of the world, universities offer environmental sciences education at the bachelor's, master's, or PhD level. This does not mean, however, that all challenges involved in implementing environmental sciences as an academic curriculum have successfully been solved. The wide range of relevant topics and the interdisciplinary character of environmental sciences curricula pose potential problems to curriculum and course developers, as well as to students. A real danger is that environmental sciences programs may lack curricular depth and coherence and that their students could be exposed to a superficial hodgepodge of competing disciplinary perspectives on environmental issues (Soulé and Press 1998).

These problems have been addressed and strategies for coping with them have been presented in several studies (see e.g., Soulé and Press 1998; Maniates and Whissel 2000; Vedeld and Krogh 2005; Chapman 2007). Among these studies, however, there are few in which the use of conceptual models for structuring academic environmental sciences education was elaborated on. This is remarkable because models play a crucial role in structuring environmental sciences research. In the past, such models have repeatedly been proposed as major instruments for obtaining insight into environmental problems and solutions and as a unifying framework in environmental sciences education (Macinko 1978; Petak 1981; Udo de Haes 1991; Udo de Haes and Heijungs 1996; Janssen et al. 1990; De Groot 1992). As we will demonstrate, such models are also more frequently applied in environmental education than the lack of coverage in the literature might suggest.

In this article, we review the merits of conceptual models as tools for integrating knowledge of environmental issues and for clarifying the process of environmental sciences research. Therefore, the following guiding questions are addressed in this article: What major conceptual models may have been used implicitly or explicitly as unifying frameworks in environmental sciences research and education? What can be learned from comparing and analysing these models about their potential roles in structuring environmental sciences education?

Our analysis is based on literature research and on our personal experiences and communications. For more than three decades, we have been intensively involved in the development of the environmental sciences curriculum at Wageningen University and have remained in close contact with the developers of many similar curricula worldwide.

In the following sections, we first address the characteristics of environmental sciences education, in order to delineate the focus of our study within the rich and variegated landscape of higher education about environmental issues. Second, we discuss conceptual models and their role in environmental sciences and education. Then, we describe the major types of conceptual models used in environmental sciences over the last forty years that are relevant for the educational context. To illustrate the use of these models in education we present a few explicit examples in separate boxes. When discussing how to apply the models to environmental problems, we will use the general examples of 'fisheries, fish stocks, and the conservation of marine resources'. In the last part of this article, we compare and discuss the models and identify consequences for contemporary environmental sciences education.

3.2 Characteristics and challenges of environmental sciences programs

Fuelled by an increasing scientific and societal attention to environmental issues, a widely diverging set of higher education environmental programs has been developed over the last four decades (e.g., for the United States Maniates and Whissel 2000; Vincent and Focht 2009; e.g., for the Netherlands Copius Peereboom and Bouwer 1993; Ginjaar and Zijderveld 1996; Schoot Uiterkamp and Leroy 2008). Many of these programs are labelled *environmental science(s)* or *environmental studies* but similar programs are also offered under labels such as *ecology, resource management, environmental management, land use planning,* or *human geography* (see e.g., Vedeld and Krogh 2005; Kainer et al. 2006; QAA 2007). Before we embark on analysing conceptual models, it is important to characterize the different types of programs and to specify the scope of the present article.

An approach frequently used to distinguish environmental programs is to look at the disciplines involved. An environmental degree program can be situated in a triangle covered by the natural sciences, the social sciences, and the humanities (Maniates and Whissel 2000). In the Anglo-Saxon tradition 'environmental science' (or sciences) often signals an emphasis on natural sciences (including ecology, toxicology, geology, hydrology and meteorology) whereas ‘environmental studies’ indicates an emphasis on social and policy studies and humanities (Vincent and Focht 2009). A similar distinction is used by an expert group that defined ‘subject benchmarks’ of environmental sciences programs for the UK Quality Assurance Agency for Higher Education (QAA). They identified the study of the relationship between human systems and Earth systems as a key feature of environmental sciences programs, and located environmental sciences programs between Earth sciences, which are focused on the study of the Earth systems (or the biophysical environment), and environmental studies, which are focused on the human systems (QAA 2007). As was demonstrated by the positioning of environmental sciences between biophysical systems and human systems, the emphasis on natural sciences in environmental sciences programs is relative, not exclusive. Studying the interactions between Earth systems and human systems is generally highlighted as a central characteristic of environmental sciences programs (Vincent and Focht 2009). Environmental sciences programs notwithstanding the differences in emphases, will therefore typically contain a broad range of disciplines from different corners of the triangle.

In their review, Vincent and Focht (2009) presented another interesting principle for distinguishing programs. This principle is based on the perspective that guides curriculum design. They identified three distinct but not opposing perspectives: (i) the perspective of *the environmental scientist*, which refers to a curriculum that is anchored within a single discipline such as chemistry or biology; (ii) that of *the environmental citizen*, in which a broad curriculum that includes the natural sciences, social sciences, and the humanities is favoured; and (iii) that of *the environmental problem solver*, a curriculum in which the aim is to educate environmental professionals, who are able to use systems approaches and to draw on insights and tools from various disciplines in order to address complex environmental issues.

These three perspectives help to further specify the scope of the present article. We will investigate the use and meaning of conceptual models in programs in which natural and social sciences are combined within a curriculum with an *environmental problem solver* perspective. Analysing and designing solutions to environmental problems by integrating knowledge from different disciplines is a key component of such programs. We have further limited our scope to programs at the university level (undergraduate and graduate). When we discuss disciplinary and interdisciplinary knowledge, our focus is on both the natural and the social sciences (including economics) and less on the humanities, although some of the issues discussed will be relevant to the latter, too.

The characteristics of such an environmental sciences program induce two interrelated challenges for curriculum and course developers. The first challenge concerns the structure of the program: How does one design a curriculum that is coherent while including various disciplines? Environmental sciences programs often encompass courses or course tracks from particular disciplinary angles, together with integrating courses, seminars and work groups (Maniates and Whissel 2000). But which disciplines should be central in the curriculum, and how far should students be educated within each of them? What is the proper place for integrating elements, and how can these elements be organized? And last but not least, how can students gain an overview of this structure, so that they can understand how specific course contents fit within the bigger picture? This challenge of program structuring has been illustrated in many studies (e.g., Soulé and Press 1998; De Groot and De Wit 1999; Maniates and Whissel 2000; Chapman 2007; Vincent and Focht 2009).

The second challenge is teaching integrated problem-solving. How can students be stimulated to develop the ability to analyse and solve complex problems? This second challenge follows from the previous one. It is not sufficient that students acquire relevant combinations of disciplinary knowledge and skills and participate in integrating courses or workshops. In doing so, they also need to learn how to integrate knowledge and skills in dealing with complex environmental problems (i.e. problems characterized by uncertainties, diverging social interests, and conflicting views on the nature of the problem and the best ways to solve it). This challenge has also been addressed in many studies (see e.g., Scholz and Tietje 2002; Vedeld and Krogh 2005; Fortuin and Bush 2010).

In exploring the prospects of interdisciplinarity and transdisciplinarity, Pohl and Hirsch Hadorn (2008) and Klein (2008) pointed at several aspects of learning: Students need to be able to grasp the complexity of human and Earth systems; students need to acknowledge the political and ethical aspects of dealing with such problems; students need to be aware of various scientific and non-scientific perspectives, methods and approaches; students need to be able to communicate over the boundaries of disciplines and to see the importance of mutual learning; and students need to learn how to assimilate broad ranges of factors to come up with an integrated understanding. In this article, we explore the potential of conceptual models to help in these crucial learning processes.

3.3 Searching for models in environmental sciences education

Conceptual models, as we use them here, are abstract representations of reality. They are usually depicted as two-dimensional diagrams consisting of circles or boxes showing the main elements or variables of a system and lines or arrows explaining the relationships among these elements. The elements can be qualitative or quantitative. Their relationships may be mathematically defined but may also consist of other, more loosely defined sorts of influences. Quantitative, mathematical models are almost always used in computerized forms to facilitate the calculation and graphical presentation of results. Because of the increasing availability of information and communication technology facilities, such models are increasingly used in education. Qualitative modelling, with or without computer support, can also be used successfully in education. Examples are the so-called 'mind maps' and 'concept maps'. Novak and Canas (2008), for instance, described the use of concept maps in education and argued that these concept maps can help students structure, retrieve and construct knowledge, which thereby substantially improves the learning process.

In the literature on interdisciplinary environmental research, conceptual models are frequently put forward as vital tools. They can provide a common framework to analyse and describe complex systems, such as socio-ecological systems, and to integrate knowledge from different disciplines (Ostrom 2009). They can be important for bringing together different disciplinary perspectives and terminology (Leemans 2008). They can also help to define a common structure for an interdisciplinary research project that consists of different sub-projects. Such a model can help identify the main components of the problem area to be addressed and can also facilitate the distribution of work among the researchers involved (Olsson and Sjöstedt 2004). Using similar arguments, several other authors have advocated the use of conceptual models as heuristic tools in a collaborative research project, to assist the integration of knowledge and the framing of the problem, as well as to improve the communication among scientists with different backgrounds (e.g., Heemskerk et al. 2003).

Given these arguments, it is plausible that conceptual models could also be useful in overcoming the challenges of interdisciplinary environmental education, as it was described in the previous section. Several authors have, indeed, advocated the use of 'unifying' models to help clarify the domain of environmental sciences and to help integrate different types of knowledge in researching environmental problems (Petak 1981; Janssen et al. 1990; Udo de Haes 1991; De Groot 1998; Scholz and Binder 2003; Tapio and Willamo 2008).

In order to identify conceptual models that could serve these purposes, we reviewed the literature in a general science database (Scopus) and in an educational database (ERIC). We searched for models that met the following criteria: (i) The model must be sufficiently generic to cover the key components of environmental science, (ii) the physical and social aspects of the environmental sciences must be included in the model, (iii) the integration of scientific disciplines in environmental research must be addressed, and (iv) the model must be operationally applied in an environmental sciences curriculum or course.

The results surprised us. Only a few models met these criteria. Clearly, there is an abundance of literature on multi- and interdisciplinarity in environmental sciences. However, we did not search for models that were used in a particular environmental sciences *research project* and that were tailored for that project. These models are likely not generic enough to provide an overarching view of complex environmental problems and interdisciplinary environmental research. There are also many publications on frameworks used to explain the *teaching and learning processes* in an interdisciplinary context in a curriculum or specific course (e.g., Kainer et al. 2006; Ivens et al. 2007). Although these frameworks can definitely be helpful for students, we did not include them because they were not focused on environmental sciences and research. We found remarkably few publications on the types of models we were interested in- that is generic models that could help curriculum and course developers and students structure environmental sciences or interdisciplinary environmental research and that could be used in the development of environmental sciences curricula.

The models we retrieved can broadly be divided into two categories: domain models and process models. Domain models are conceptual models that structure the domain of environmental problems. In other words, these models provide an overview of the subject areas that the environmental sciences deal with. Process models are models that structure the process of environmental research, that is, they depict the different steps in an environmental research process and clarify how these steps are related to the societal processes important to the research (i.e. how they relate to environmental problem-solving). In the next section, we will further examine these two categories. Given the scarcity of publications on these models, we cannot provide a comprehensive overview of generic models used in environmental sciences education. Rather, we will focus on four examples of models - two of each category - that are applied in education and that we consider to be well developed and fairly representative for the scope of our investigation.

3.4 Domain models

'Domain models' are conceptual models that structure the domain of environmental sciences. They describe components or processes involved in environmental problems. These models thus structure the *objects* of environmental research. The most basic domain models describe the different compartments of the physical environment (e.g., hydrosphere, lithosphere, atmosphere, biosphere) and their links with sociocultural systems. A different, somewhat affiliated type of domain models is the level model, which distinguishes different levels in the physical environment - for example, from atoms and molecules to cells, organisms and ecosystems. Humans and societies can also be added to such hierarchies, which are often inspired on Von Bertalanffy's General Systems Theory (Von Bertalanffy 1968). Such models are frequently taught in environmental courses but are generally not used as overarching models for environmental sciences curricula. An obvious reason for this is that they ignore processes of causation of or action against environmental problems.

3.4.1 DPSIR and other causal chain models

A major group of domain models is influenced by the PSR (pressure – state – response) model developed by the Organisation for Economic Co-operation and Development (OECD, 1993). This model distinguishes ‘pressures’ from human activities that affect the system’s ‘state’ (i.e. the quality and quantity of natural resources) and societal ‘responses’ (i.e. environmental and other policies, and changes in awareness and behaviour) to mitigate the environmental impacts. After its publication in the early 1990s, it soon became a well-known and widely used framework.

The European Environment Agency expanded the PSR model into the DPSIR (driving forces – pressure – state – impact – response) model to structure the use of environmental indicators and harmonize environmental policy reporting. The DPSIR model added the social and economic developments denoted as 'driving forces' and makes a distinction between changes in the system's 'state' of the environment and 'impacts' on ecosystems, resources, materials, and human health. Societal 'response' may provide feedback on the driving forces, but also on the pressures, state, or impacts directly, through adaptation or curative action (Smeets and Weterings 1999, Figure 3.1).

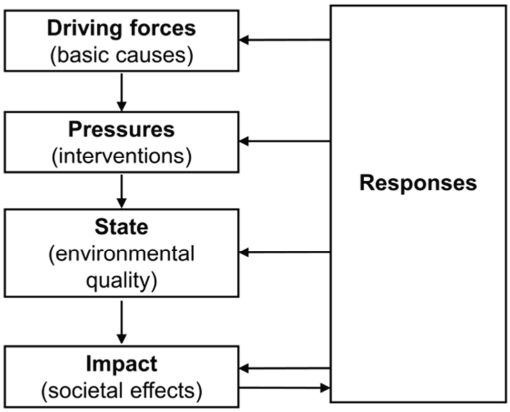

Figure 3.1 The DPSIR (driving forces-pressure-state-impact-response) framework (adapted from Smeets and Weterings, 1999)

The DPSIR model can be used to analyse an environmental issue, as we illustrate here with the example of 'depleted fish stocks'. Examples of driving forces that deplete fish stocks are the rising demand for seafood and the recent increase in fishing fleet size and efficiency, which has resulted in an enormous growth of the exploitation of marine fishes (pressure). Fish stocks have been seriously declined or even depleted in many parts of the world (state). Fish stocks depletion has an impact on people who depend on seafood as their main source of protein and on people who depend on fishing for their income. To cope with these problems, several kinds of solutions (responses) have been proposed, such as catch restrictions, gear modification and marine protected areas.

In the Dutch debate on the domain of environmental sciences in the 1980s and 1990s, cause-effect frameworks similar to the DPSIR model were proposed, such as the *environmental* *problem chain* (EPC), which was quite generally used in characterizing the domain of environmental sciences (see e.g., Udo de Haes 1991; Janssen et al. 1990). The EPC is a framework that describes environmental problems as a chain of the following elements: Basic causes that lead through societal activities or situations and interventions to environmental effects and finally to societal effects (i.e. effects that are considered problematic by society).

Both the PSR and the DPSIR frameworks have strong natural science bases. From a social sciences perspective, these frameworks have shortcomings, because they do not account for all the complexity of and interactions within society. In reality, responses do not 'automatically' follow an impact, and what happens within society is much more complicated than what can be illustrated by a single 'driver's box'. That is why there have been several attempts to expand the EPC and DPSIR models to include societal aspects.

Janssen et al. (1990) expanded the EPC model with an *environmental policy chain,* which mirrors the problem chain. The environmental policy chain explains where and how environmental problems are influenced by society and indicates where interventions are possible. It was developed to identify ways to regulate or mitigate environmental problems and provides an analytical tool to evaluate and design environmental policy. Although this model is useful, it lacks some of the simplicity and transparency of the DPSIR model.

Tapio and Willamo (2008) introduced the environmental protection process (EPP) framework as a more detailed version of the DPSIR model to counteract its shortcomings. Just like Janssen et al. (1990), they included the policy making process. Moreover, instead of treating society as a general abstraction and lumping all factors that affect human action together as 'drivers', they distinguished in their model three categories that affect human actions on different levels: (i) individual factors (e.g., knowledge, values, emotions, experiences, resources) (ii) societal factors (e.g., politics, administration, legislation, economy, science, education, religion, mass media, social activism) and (iii) ecological factors (e.g., landscape topography).

A common feature of all of the frameworks described so far (DPSIR, EPC and EPP) is their perspective: They all take environmental *problems* as their starting point. These problems originate in the interaction between the human system and the Earth systems. The EPC and

EPP model are used to investigate the 'root causes' more thoroughly than the DPSIR model, but in the end, all three frameworks are designed to answer three main questions (following Tapio and Willamo 2008): (i) Why are there environmental problems? (ii) What are these problems' characteristics? And (iii) in what ways can they be mitigated?

Obviously, the real world is far more complex than what can be expressed in these simple linear conceptual models. The strengths of the DPSIR-like models are, however, that they are easy to understand and that they can be used to clearly visualize the interactions between changes in the biophysical environment and human systems. They are generic and therefore suitable analytical tools for the examination of many environmental issues. DPSIR-like models are frequently used in environmental assessments and research projects and have great merits for education as well.

The DPSIR, EPC and EPP models have all been used in education to structure environmental issues and to navigate and focus in the broad range of relevant disciplines (Boersema and Reijnders 2009; Bouwer and Leroy 1995; Tapio and Willamo 2008). At Wageningen University, the DPSIR model was central in the environmental sciences curriculum developed in 2000 (see Box 3.1). In Finnish environmental sciences education the EPP model is used to structure an university-level basic course textbook (Tapio and Willamo 2008) (see Box 3.2). These models are thus used as a framework to assist students in seeing connections between different elements of a curriculum or course, and as conceptual tools that assist those students in analysing an environmental problem and identifying ways to mitigate it.

Box 3.1 The DPSIR model and the Wageningen environmental sciences curriculum

Until the late 1980s, the environmental sciences curriculum of Wageningen University was focused on pollution problems, and the source – distribution - effect model was dominant in the study. Courses mainly addressed the emission of environmental pollution into the environment; the distribution and transformation of this pollution in water, air, and soil; and the effects of pollution on public health and ecosystems. Students could specialize in water, air, and soil quality; environmental technology, environmental toxicology; and environment health. Within the environmental technology specialization the focus was mainly on wastewater treatment. Since the 1980s, courses in environmental policy and company environmental management have gained importance, and, in addition to cleaning and sanitation, prevention became a key element of environmental technology. Furthermore, the integration of compartments and integration of environmental issues with spatial planning issues became more prominent. In 2000, environmental systems analysis, environmental policy the (study of driving forces of environmental problems), and environmental management (the study of the response of society to the impacts of environmental problems) were added as new specializations to the curriculum. As an overarching model of this curriculum, the source – distribution - effect model was replaced by the DPSIR-model.

Box 3.2 The EPP model in Finnish environmental sciences education

The environmental protection process (EPP) model is used in Finland to structure environmental sciences education. The model is broad in scope, but it helps its users to navigate and focus within the many disciplines relevant for environmental sciences. The EPP model takes a problem-oriented approach, just like the DPSIR model. Starting with an environmental problem, such as air pollution in a particular city, the EPP model helps determine which knowledge from, for instance, cognitive psychology, environmental economy, environmental sociology, environmental chemistry, environmental health, or environmental technology, is relevant enough to be taken into account; namely the knowledge that is useful for understanding why there is air pollution in the city (e.g., increased traffic caused by urban sprawl), what the characteristics are of this air pollution (e.g., mainly carbon monoxide, oxides of nitrogen, volatile organic compounds and particulates caused by car traffic), and how it can be mitigated (e.g., improved public transportation). The model is not meant to provide an overall theory. Instead it is used as a broad, flexible framework, open to different kinds of theories and interpretations (Tapio and Willamo 2008).

3.4.2 The ecosystem based model of the Millennium Ecosystem Assessment

Since the turn of the twenty-first century, sustainability has become more and more important as a guiding principle in environmental sciences education (see e.g., the textbooks by Botkin and Keller 2000; Nebel and Wright 2000; Wright 2005; Cunningham and Cunningham 2006; Miller and Spoolman 2008). A framework that fits well within this sustainability approach is that of the Millennium Ecosystem Assessment (MA) framework (2003). Crucial to this framework is the use of the concept of 'ecosystem services' as a way of explaining the shorter and longer-term linkages between people and the environment at local, regional and global levels. Humans depend on the benefits they obtain from ecosystems (i.e. the ecosystem services) for their well-being. In the MA framework distinctions are made between provisioning services, regulating services, cultural services, and supporting services (see Figure 3.2). Marine ecosystems, for instance, provide vital food resources for millions of people but also provide regulating services, such as carbon sequestration and waste detoxification. For many fishing societies, in which fishing is an inextricably part of the livelihood, fish resources not only provide food and income but also have important cultural meaning, and therefore provide cultural services. Changes in these provisioning, regulating, and cultural services affect human well-being through impacts on the basic material needed for a good life, health, good social and cultural relations and security. These constituents of well-being are in turn influenced by and have an influence on the freedoms and choices available to people (Millennium Ecosystem Assessment 2003). Therefore, instead of investigating the impacts of human actions on the environment (e.g., the exploitation of fish stocks) and instead of treating ecosystems and the environment as externalities to the human system, as is often done in environmental sciences models (see, for example, DPSIR and related models) humans are considered an integral part of ecosystems in the MA framework.

Whereas we found that the DPSIR model is focused on the problematic aspects of the relationship between human and environment systems (e.g., the depletion of fish stocks), the MA framework highlights the opportunities that nature (biodiversity) provides for improved quality of human life (e.g., the various marine ecosystem services). It takes biodiversity as its basic starting point. By focusing on ecosystem services and human wellbeing, the MA framework takes a more positive and future-oriented perspective than the problem-oriented DPSIR approach. Moreover, by identifying various categories of services, the MA framework assumes that nature provides a broad range of positive services. Because it includes the category of cultural services and because it takes a broad view of human well-being, it also integrates non-material services. In this way the role of culture in dealing with nature is highlighted. This is completely lacking in DPSIR-like models.

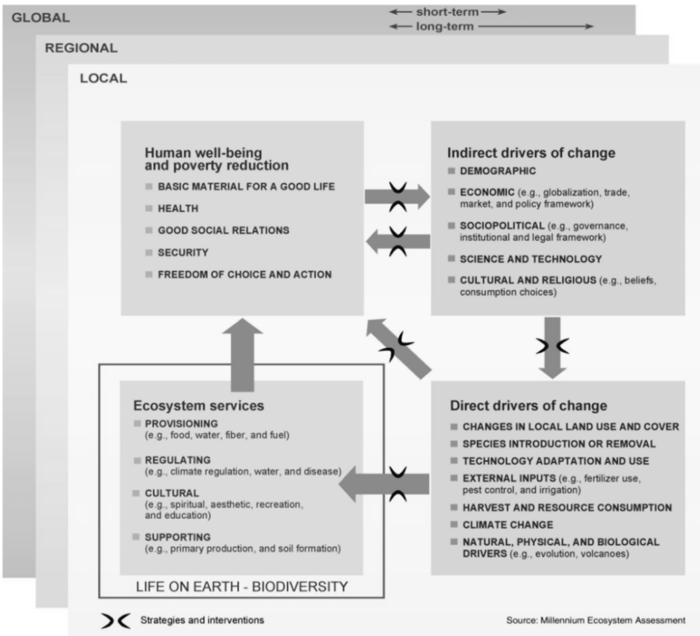

Figure 3.2 Millennium Ecosystem Assessment framework (MA 2003)

Just a few years after the release of the MA, it is used in university education all over the world. Reid (2006) did a survey among individuals that were involved in the MA process to investigate the impacts of the assessment. He found that the MA material and the MA conceptual framework are being used extensively in university courses and curricula. The material is not only used in environmental sciences (see Box 3.3) but also in courses on conservation biology or ecology and in courses addressing sustainability and globalization. The MA framework appears to be suitable for teaching global issues, but it can also be used to teach resource use in a specific region, to analyse drivers of change, and to identify opportunities for intervention. Reid (2006) did not address whether the conceptual framework had an impact on whole curricula, but it is clear that the framework was rapidly adopted and integrated into university courses. This is also illustrated by environmental textbooks that have recently been published (e.g., De Kraker 2007; Miller and Spoolman 2008; Wright 2008).

Box 3.3 The MA framework in Wright's environmental sciences textbook

In the ninth edition of his textbook *Environmental Science,* Wright (2005) introduced the Millennium Ecosystem Assessment (MA, 2003) framework for the first time. The MA and its conceptual framework are explained in the first chapter, and new *integrative* themes that are influenced by this framework, are introduced: (1) *ecosystem capital*, (2) *policy and politics* and (3) *globalization* (Wright 2005, p. xviii). These integrative themes provide important threads for the textbook and link the different subjects and chapters, together with three *strategic* themes that were retained from the eighth edition: sustainability, science and stewardship.

In the 10th edition (Wright 2008), the MA is fully integrated into Wright's textbook. Again, the MA and its framework are introduced in the first chapter and the integrative and strategic themes are kept, but in this edition the findings from the MA are used throughout the textbook to illustrate or underpin the author's message and to interconnect different subjects and issues.

The 11th edition (Wright and Boorse 2011) starts with the introduction of a framework for a sustainable future. A chapter on economics, politics, and public policy that used to be one of the last chapters has become part of this framework. The authors have chosen to go back to the three themes for environmental sciences that they used in earlier editions of the book: "*sound science*, the basis for our understanding of how the world works and how human systems interact with it; *sustainability,* the practical goal that our interaction with the world should be working toward; and *stewardship,* the actions and programs that manage natural resources and human-wellbeing for the common good" (Wright and Boorse 2011, p. xvi).

Overall the MA framework helped to further articulate and illustrate old ideas. It did not represent a revolutionary, new way of thinking but did help to label earlier perceptions. The MA framework was apparently less appropriate for the organization of the full content of the environmental sciences textbook. The structuring value of the MA framework was mainly its role as a recurring theme: as a typical example (paradigm) of sound science for sustainability.

3.5 Process models

In this section, we describe 'process models' that structure the process of environmental research (in particular research that addresses societal problems). The models of this category do not describe the components or processes that are the object of environmental research; they depict the steps in an environmental-research process and its relation with societal processes. As we explained above, a characteristic of environmental sciences research is its link to societal problems. Integration of knowledge and moral and ethical aspects related to societal problems are of importance for environmental research. The process models may be applicable to other (problem-oriented or interdisciplinary) research as well. In this section, however, we focus on those models that are sufficiently generic to cover the key components of the environmental-research process.

3.5.1 Models for problem oriented research

In the 1980s several models for problem-oriented research were developed, usually by combining models in which the different steps in research were described with models in which problem solving was described. A model that is used in environmental sciences education and that is characteristic of this period is the model for problem oriented research developed by Van Koppen and Blom (1986, Figure 3.3). This model highlights the point that, in problem-oriented research, science becomes involved in a societal process of problem solving. Scientists take part in this process, but the logic of problem solving and the logic of scientific research are not the same. Societal actors determine whether there is a problem (e.g., fish stocks are declining), and are responsible for solving the societal problem by performing a successful intervention (e.g., the implementation of catch restriction or protected areas), whereas scientists are responsible for generating reliable knowledge to support these problem definitions and interventions. Scientists can, for instance, investigate the effects of the exploitation of marine resources on species composition, size structure, biomass, and other ecosystem properties, or those of the impacts or minimum size of protected areas. Scientists, when they are doing research, follow the logic of the empirical cycle of scientific research (the right side of Figure 3.3). To translate societal questions on analysis and strategy into scientific research questions, scientists use specific frames and models (e.g., ecosystem models, “Scientific model” in Figure 3.3) that usually are a simplified representation of the problem domain.

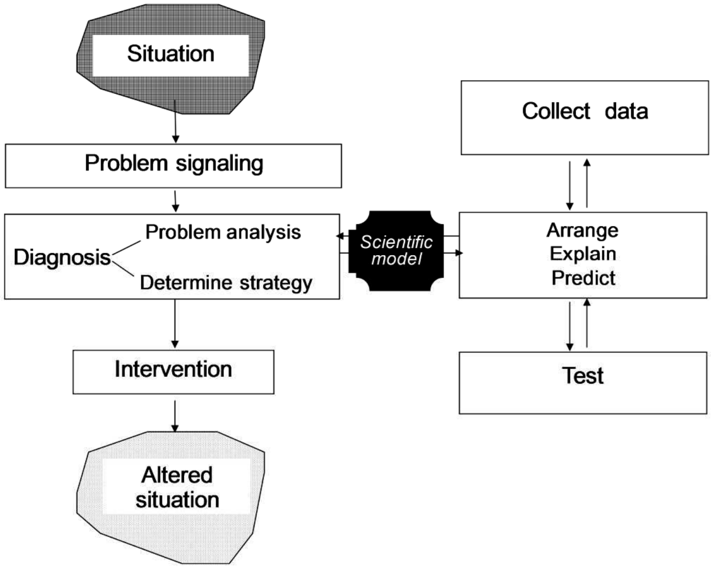

Figure 3.3 The van Koppen and Blom (1986) model for problem-oriented research.

The van Koppen and Blom (1986) model helps students to understand the differences between problem solving as a societal process and scientific research, and to distinguish different steps that are relevant to problem-oriented research. For instance, it helps them to see that defining a problem is a normative process determined by stakeholders, that their scientific models provide only a partial view on the problem domain, and that a good scientific outcome as such does not solve the societal problem. The results of the ecosystem models do not solve the problems of resource depletion or the difficulties related to the implementation of catch restrictions or protected areas.

The van Koppen and Blom (1986) model does not explicitly address interdisciplinarity. Although students who do problem-oriented research might realize that knowledge from scientific disciplines and other sorts of knowledge play a role in tackling the societal problem, the research they conduct can be based on a purely disciplinary model.

Several other authors have made efforts to further detail and elaborate models of the environmental-research process. An elaborate example is the problem in context (PiC) model developed by De Groot (1998). The PiC model encompasses the whole domain of environmental sciences, including the natural sciences, the social sciences and the humanities, as well as normative elements related to societal problems. At the same time, the PiC model provides a methodological framework designed (i) to analyse perceived environmental problems; (ii) to explain their societal root causes, (iii) to identify any involved actors, their options, and motivations; and (iv) to create and evaluate solutions for these problems. De Groot (1998) tried, in fact, to combine the domain of environmental sciences and environmental research and problem solving into one comprehensive model. The PiC model is used in education, but its comprehensiveness and complexity makes it difficult to implement.

Both the van Koppen and Blom (1986) model and the PiC model have been used in environmental sciences education in the Netherlands. They are introduced to students in courses in which the students have to practice environmental research and to reflect both on the societal and ethical implications of that research, as well as on their role as scientists in solving a societal problem. A methodological framework turned out to be necessary to help the students structure their work and their reflection (Van Koppen and Blom 1986) (see Box 3.4).

Box 3.4 The van Koppen and Blom (1986) model for problem oriented research in a bachelor's-level course

The van Koppen and Blom (1986) model (Figure 3.3) is used in the bachelor's level course Environmental Project Studies at Wageningen University. The aim of this course is to acquaint students with solving an environmental problem, with carrying out scientific research, and with the relationship between science and society.

In this course a team of four students analyses a real life environmental problem proposed by a non-academic professional (e.g., from a local government or NGO). This professional - the commissioner of the project - proposed the problem and is responsible for the interventions to solve the problem (see the left side of Figure 3.3). The students discuss the problem with the professional, design a research plan, and execute this research plan (see the right side of Figure 3.3). Usually, they review literature, interview people, or conduct practical research to collect data and analyse them. The team arranges its results and formulates conclusions. Finally, the team presents the professional with a written report on the results of their research. The professional, who is responsible for dealing with the societal problem, decides what to do with the students' results and communicates this to the students.

One student project was related to the problem of global warming caused by the high consumption of fossil fuels. To mitigate this problem the European Union has proposed gradually increasing the percentage of biodiesel in diesel fuel to 10% by the year 2020. A Dutch firm with commercial interests in sustainable energy wanted to understand the possible contribution of sustainable palm oil in this strategy. The main research question that the students formulated was: "How much can the production of sustainable palm oil contribute to the European diesel-fuel market by the year 2020?" Their sub-research questions were related to the developments of the diesel-fuel market in Europe and the palm oil market in the world, as well as to the possibilities of a sustainable palm oil production. The students did a literature review, investigated data bases and interviewed experts. One of their conclusions was that palm-oil production practice has many shortcomings. They pointed out the necessity of designing solutions to overcome the unsustainability of current palm oil production.

After conducting the research, the students reflected on their work. They discussed the societal and ethical implications of their research and their role as scientists in solving a societal problem. One of the issues that they discussed was the trade-off between the solutions proposed by the European Union to mitigate global warming and the loss of biodiversity caused by palm oil cultivation in other parts of the world. The framework illustrated in Figure 3.3 proved to be helpful for this reflection. The students realized that the design and execution of their problem-oriented research and their recommendations were partly determined by the interests and needs of the professional who proposed the problem (Fortuin and Van Es 1999).

3.5.2 Models for transdisciplinary research

In current publications on environmental sciences education and research, transdisciplinary approaches have become prominent (see e.g., Pohl 2005; Scholz et al. 2006; Regeer and Bunders 2009). Transdisciplinary research is designed to contribute to solving or mitigating complex social problems by including stakeholders. Characteristic of transdisciplinary research is that it is intended to "(i) grasp the complexity of problems, (ii) take into account the diversity of life-world and scientific perceptions of problems, (iii) link abstract and case-specific knowledge, and (iv) develop knowledge and practices that promote what is perceived to be the common good" (Pohl and Hirsch Hadorn 2007, p20). The life-world, or *Lebenswelt*, perceptions of laypeople are explicitly included in transdisciplinary research, and an intensive interaction between scientists from different disciplines and actors from society is required in all stages of the research.

Jahn (2008) developed a conceptual model for transdisciplinary research (see Figure 3.4). We introduce it here because it provides a characteristic and clear representation of transdisciplinary approaches. In this model for transdisciplinary research, there is still a distinction between dealing with a societal problem (see the left column in Figure 3.4) and doing scientific research (see the right column in Figure 3.4), but during the transdisciplinary research process, the interaction between scientists and societal actors is very intensive (see the middle column in Figure 3.4). The example of the overexploitation of marine ecosystems and the depletion of fish stocks can again illustrate this. Several management tools have been proposed and implemented to mitigate these problems. These management tools are based on scientific research in disciplines such as fisheries and conservation biology. Indeed, catch restrictions, gear modification and protected areas have helped to reduce the exploitation rates of fish stocks. The results are, however, very different in different ecosystems (Worm et al. 2009). Apparently, the interaction among fish, fisherman, and management system is very complex, and context-dependent solutions are needed. Such solutions must involve the local characteristics of the fisheries, ecosystem, and governance system. The development of these context-dependent solutions can be the starting point of a transdisciplinary research process.

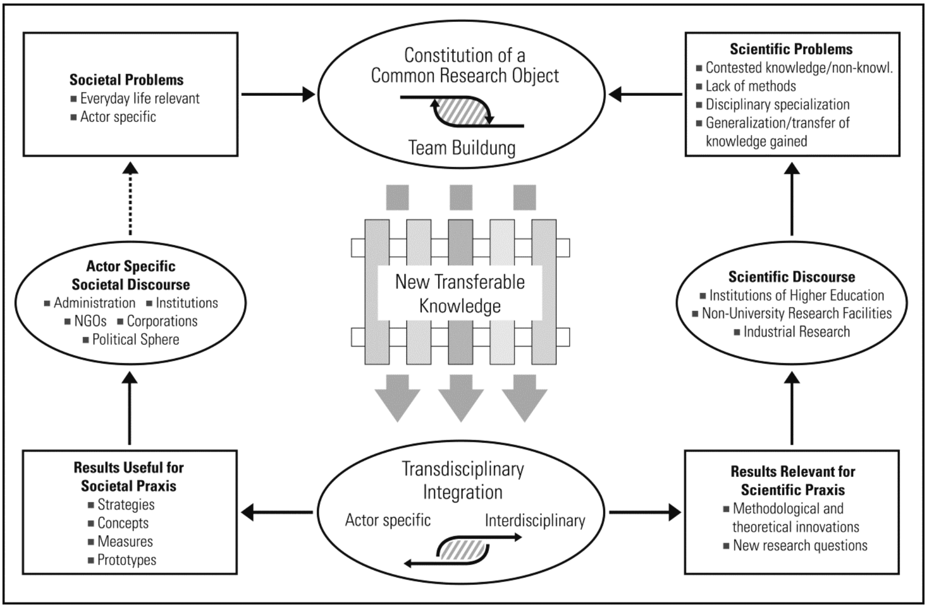

Figure 3.4 The Jahn (2008) model for transdisciplinary research

This process starts with a problem-framing phase, in which a team of scientists and societal actors jointly formulate a common research object (e.g., develop strategies for sustainable fisheries) and (disciplinary or interdisciplinary) research questions. Consequently, different subprojects are executed for which knowledge from several disciplines (e.g., ecology and economics) and knowledge from practice (e.g., local fisheries practices) is needed. This is also the phase at which new knowledge is produced or existing knowledge is combined or integrated. The compatibility among the different subprojects and the possibility of integrating these projects are of special concern (“New Transferable Knowledge” Figure 3.4).

Finally, at the last phase of the research process, transdisciplinary integration, strategies, innovations, and transformations should be developed to address both societal and scientific problems (Jahn 2008). Although the Jahn (2008) model for transdisciplinary research is quite recent, it is already used in education (see Box 3.5).

Box 3.5 The Jahn (2008) model for transdisciplinary research in an interdisciplinary course at the Technische Universität Darmstadt

The Jahn (2008) model for transdisciplinary research is used by Stieß and Field in their course, 'Social Ecology – Theory, methodology and praxis of transdisciplinary research' at the Technische Universität Darmstadt. The course is part of an interdisciplinary study focus in environmental sciences and was attended by students from engineering, and the social and educational sciences. Stieß explained that, on a general level, the model was used to introduce and explain characteristic stages of the transdisciplinary research process and to discuss basic methodological implications, such as problem - actor orientation and knowledge integration. It was also used as a tool for analysing empirical research processes in order to exemplify those characteristic stages, with two research projects of the Institute for Social-Ecological Research (ISOE) as examples. Stieß said: "We found it very helpful to use the model as a device to link the discussion on a conceptual level to the analysis of more tangible empirical examples. This helped the students to better understand the specific features of interdisciplinary and transdisciplinary research" (Immanuel Stieß, ISOE, Frankfurt am Main, personal communication, 4 April 2010).

3.6 Potential functions of the selected models

The DPSIR model, the MA framework, the van Koppen and Blom (1986) model, and the Jahn (2008) model described in this article are valuable heuristic tools that can be used to structure environmental sciences education. They are helpful because they are generic, simple, and straightforward and can be easily understood by students. The function that these models might serve in structuring environmental sciences education varies. Table 3.1 lists the potential functions as we have encountered them in the literature and in our analysis. We have also indicated our assessment of the relative strengths of the models in fulfilling these functions. We will discuss these functions and our assessment of them below.

Of the two domain models, the DPSIR model provides a better framework to structure an environmental sciences curriculum - in particular, a curriculum with an *environmental problem solver* perspective - than does the MA framework. Disciplinary scientific knowledge can be more easily located within the DPSIR model than within the MA framework. Practitioners of the natural sciences (e.g., biology, physics and chemistry) study the environmental pressures, states and impacts through the investigation of, for instance, the emission of pollutants and their effects on organisms and ecosystems. Practitioners of societal disciplines, such as sociology and economics, investigate drivers, the societal causes of environmental problems, and pressures. Those in environmental technology and environmental policy and management investigate responses in order to find ways to mitigate the problem. This 'discipline-oriented' character of the DPSIR model makes it suited to provide a framework that connects various disciplinary elements within an environmental sciences curriculum. Its 'problem-oriented' character helps to focus and to select among the abundance of disciplinary knowledge. Using the DPSIR-model as a framework of an environmental sciences program can improve the coherence of such a program.

Table 3.1 Potential functions of four conceptual models in structuring environmental sciences education

	Model			
Function of the model	**DPSIR**	**MA**	**Van Koppen and Blom (1986) model for problem oriented research**	**Jahn (2008) model for transdisciplinary research**
To improve coherence and focus of an environmental sciences curriculum	+	+-	-	-
To analyse environmental problems and solutions and to integrate divergent knowledge	++	++	-	-
To examine and guide an environmental problem-solving and research process	-	-	++	+
To examine and guide the integration of divergent knowledge in the environmental problem solving and research process	+-	+-	+	++

Note: The pluses and minuses indicate the relative strengths of the models in fulfilling a specific function.
DPSIR, driving forces – pressure – state – impact – response; MA, Millennium Ecosystem Assessment

In the MA model, however, it is possible to identify and integrate fields of study that are linked to specific services. Ecology and geology are, for instance, related to regulating and supporting services, social and cultural studies to cultural services, and agricultural sciences and mining to provisioning services. The MA framework is also one that might connect various elements or courses within a curriculum. We found, however, that it seems less suitable to structure a complete environmental sciences curriculum. Yet the MA framework offers opportunities to make connections to other areas, such as development studies as is illustrated by the use of the MA framework in courses addressing sustainability and globalization. The DPSIR model is poorly suited for analysing development issues (Carr et al. 2007).

Both domain models provide a very good framework for analysing the interactions in the human-environment systems and for integrating knowledge from various disciplines. The DPSIR-model is better suited for analysing environmental problems - in particular pollution problems. Because the MA framework takes biodiversity as its basic starting point, it is less appropriate for analysing pollution problems that do not involve biological systems (e.g., the effects of acid rain on buildings). Crucial in the MA framework is the concept of ecosystem service, which is an integrative concept itself and which allows ecologists, economists, sociologists and other disciplines to have a common language on the importance of ecosystems for human wellbeing.

Another difference between the MA and the DPSIR models is that the latter is a rather linear model. The DPSIR model includes feedback in the form of deliberate actions - 'responses' - but does not address the systemic feedback that changes in ecosystems, driven directly or indirectly by changes in human condition, might have on human-wellbeing. The MA framework is designed to allow the examination of how changes in ecosystems influence human wellbeing and vice versa. In doing so this framework takes a more dynamic perspective on the interaction between people and ecosystems than the DPSIR model does.

In both the van Koppen and Blom (1986) model for problem-oriented research and the Jahn (2008) model for transdisciplinary research the process of environmental problem solving and research are examined and the relationship between scientific research and societal problems is clearly addressed. There are three crucial and interrelated differences in how this is illustrated in the models. First, in the Jahn (2008) model the *complexity* and different perceptions of the problem and the research process are highlighted. Several research questions, which will require their own scientific methodologies, need to be formulated to tackle the full complexity of the problem. By contrast, the van Koppen and Blom (1986) model would also apply to rather simple problems that could be solved by, for example, one rather technical research project answering an important issue in the diagnosis process (e.g., establishing whether the concentrations of specific pollutants are below or above existing standards).

At some point, the diverse perspectives in the Jahn (2008) model have to come together. The *integration* of divergent concepts, scientific knowledge, and practical knowledge and needs, is explicitly addressed in this model (Godemann 2008). This is the second crucial difference between it and the van Koppen and Blom (1986) model. The latter stresses that scientific research has to fit in a sequence of problem solving but does not highlight the need for integrating different knowledge.

Finally the *role of science* in solving societal problems is illustrated differently. In the van Koppen and Blom (1986) model the domains of science (the empirical cycle) and that of society (the process of problem solving) are interrelated, but their relation is rather linear and they remain in distinct domains. The outcome of scientific research feeds into the problem-solving process where societal actors decide what to do with the results - which interventions to undertake in order to change a situation that is considered problematic. The Jahn (2008) model illustrates a continuous dialogue and interaction between the scientific world and society.

These three aspects (i.e. complexity, knowledge integration, and the role of science) are key issues in the contemporary debate on environmental sciences and illustrate the major challenges for current environmental sciences education.

3.7 Discussion

Although not all models used in academic courses are documented in the literature, we believe that the models that we have discussed, cover the major model types used in structuring environmental sciences education. The two more recent models present a broader approach to environmental sciences than do the older models, which have a more linear character. The MA model does so by taking a broad range of positive environmental services (including cultural services) and a broad view on human well-being as its core, instead of focusing on the problematic relationship between humans and the environment. The transdisciplinarity model does so by highlighting the complexity of environmental issues and by representing a continuous process of interaction between scientific research and societal problem solving. These recent shifts reflect developments in society: (i) the shift from environmental problem solving towards a more systemic view of the human - environment relationship and its complexity, (ii) the increased interest in sustainability or sustainable development, and (iii) the changing views on the role of science in dealing with societal issues. Instead of adding specific insights to the analysis of societal problems or providing technological implementations, the role of science is seen as enhancing 'the process of the social resolution of the problem, including participation and mutual learning among stakeholders' (Funtowicz et al. 1998, p104). If students must become aware of the various approaches to frame environmental issues and to illustrate and explain the developments in this field, these models are very suited for their education.

The conceptual models that students are exposed to during their education will affect the way they learn to look at human-environment systems and the role of science. Svarstad et al. (2008) clearly illustrated that the DPSIR framework is not a value-free tool but favours specific types of discourses. Therefore, the models that students use during their education will influence the ways in which they will frame environmental issues in the future. For environmental scientists, being aware of one's own framework is crucial, because it is a prerequisite for being able to reflect on it and to discuss frameworks with scientists from other disciplines (Fortuin and Bush 2010). Therefore, the models underlying a curriculum should be made explicit to students, and the students should critically reflect on these models.

3.8 Conclusions

Simple, generic conceptual models are valuable for environmental sciences education. They provide an easy to understand framework that improves the coherence and structure of an environmental sciences curriculum. Seeing the connections between different elements within a curriculum is important for curriculum and course developers and for students. Moreover, conceptual models can provide a common framework to analyse environmental problems and to integrate knowledge, and they can be used to communicate across disciplines.

It is possible to distinguish between domain models and process models. Domain models describe the components or processes involved in environmental problems. They indicate the subject area of environmental sciences. Process models depict the process of environmental research and the relation with societal problems. Both types of models are meaningful for environmental sciences education, but they have different strengths. Domain models can be used to improve the coherence and focus of an entire curriculum. In an individual course, these models can be used as an illustrative and typical example of how conceptual models can be used as frameworks for dealing with complexity and for integrating divergent knowledge. As such, their structuring value goes beyond the individual course. Process models can be introduced along with a research project on a realistic societal problem. The models discussed in this article can help students reflect on their research activities and on the characteristics of environmental sciences research. They also offer students a framework to analyse and discuss the role of science in solving environmental problems and the contribution of various disciplines to tackle environmental issues.

Although all four models presented in this article are valuable for structuring environmental sciences education, none of them is sufficient to become the only unifying framework. Rather, specific models should be used at specific moments with the more complex models (e.g., the MA framework, the Jahn (2008) model) situated at later stages in a curriculum. In the beginning of a study program (e.g., Bachelor of Science level), the older, more linear models (e.g., the DPSIR model and the van Koppen and Blom (1986) model) can guide students in their first stages of mastering environmental sciences. These simple models are still adequate for many environmental issues. Later, in the master's and PhD phase, more-encompassing and complex integrative conceptual models that include feedback systems and interactions between phenomena on different temporal, geographical, and organizational scales should be used. Models in which the full complexity of human-environment systems is addressed and in which the need of integrating divergent perspectives to fully comprehend this interaction is indicated should be part of graduate and postgraduate environmental sciences education.

It is essential that students be exposed to a range of conceptual models during their education, because such a variety is instrumental in making the students aware of the various approaches to framing environmental issues and in illustrating and explaining how this framing has changed over time. By applying and reflecting on these conceptual models, students become aware of the complexity of the human-environment systems and the role of science in dealing with environmental problems that affect society. That is why we strenuously advocate the use of different conceptual models for students at different stages of their education.

4 The contribution of systems analysis to training students in cognitive interdisciplinary skills in environmental science education

Abstract

Professionals in the environmental domain require cognitive interdisciplinary skills to be able to develop sustainable solutions to environmental problems. We demonstrate that education in environmental systems analysis allows for the development of these skills. We identify three components of cognitive interdisciplinary skills: (1) the ability to understand environmental issues in a holistic way, taking into account the interplay of social and biophysical dynamics; (2) the ability to connect both the analysis of environmental problems and the devising of solutions with relevant disciplinary knowledge and methodologies; and (3) the ability to reflect on the role of scientific research in solving societal problems. Environmental systems analysis provides tools, methods and models to assist in framing complex environmental issues in a holistic way and facilitates the integration of disciplines. Systems analysis also supports reflection by making students aware that a system always represents a simplified model and a particular perspective. Through the analysis of a collection of BSc students' 'reflection papers' we identify two major challenges in teaching these cognitive skills: (1) to train students to not just follow a systematic approach but acquire a systemic view; and (2) to train students to be reflexive about systems analysis and the role of science. We recommend that training in cognitive skills starts early in a study program.

Based on Fortuin, K.P.J., C.S.A. van Koppen, and C. Kroeze. 2013. The contribution of systems analysis to training students in cognitive interdisciplinary skills in environmental science education. *Journal of Environmental Studies and Sciences* 3 (2): 139-52. doi: http://dx.doi.org/10.1007/s13412-013-0106-3.

4.1 Introduction

The design of sustainable solutions for environmental problems calls for university-level professionals with specific competencies. Many course and curriculum developers of undergraduate and graduate programs within environment and sustainable development face the challenge of training students in these competencies (see e.g., Jacobson and Robinson 1990; Scholz et al. 2006; Fortuin and Bush 2010; Pohl and Hirsch Hadorn 2008; Newing 2010). The competencies required include the theory and understanding of a particular domain (e.g., disciplinary and interdisciplinary knowledge), as well cognitive abilities (e.g., critical thinking), technical and analytical abilities (e.g., lab skills) and general skills (e.g., written and oral communication, team work, project management). These competencies are essential to a professional in a specific domain and thus define what an undergraduate or graduate needs to have gained during his/her education.

In the context of science and education for sustainability there have been recent discussions on competencies (see e.g., Martens 2006; De Kraker et al. 2007; Rieckmann 2012). In these discussions, the need to specify core competencies to successfully contribute to sustainable development and to address these explicitly in the educational curriculum is widely acknowledged. The descriptions of competencies offered in literature are, however, very general and broad, encompassing a wide range of knowledge and skills. For example, De Kraker and co-workers define as a key competency for academic professionals to contribute to sustainable development “their ability to deal, think, communicate, learn and collaborate across the boundaries that divide a diversity of perspectives” (De Kraker et al. 2007, p107-108). They introduce the concept of ‘*transboundary competence*’ and define this as ‘the ability to take a whole systems-oriented, interdisciplinary, participatory or transdisciplinary, international, cross-cultural, cross-scale, future oriented, and creative approach to sustainability problems’ (ibid: p108). Rieckmann (2012) identifies systemic thinking to handle complexity, anticipatory thinking and critical thinking as key competencies for future education. These descriptions of key competencies are valuable, but at the same time too broad and abstract to implement into an interdisciplinary environmental sciences course or curriculum. We argue that these key competencies need to be specified.

Vincent and Focht (2011) make a useful step towards specifying core competencies in their study of interdisciplinary environmental degree programs. They distinguish three interdisciplinary knowledge areas: (i) natural sciences; (ii) coupled human-nature systems; and (iii) economic development. They also identify two integrated skills areas; (i) problem analysis skills; and (ii) problem solutions and management skills. Cognitive skills are highlighted as a key element for both the analysis of environmental problems as well as the formulation of solutions.

Vincent and Focht (2011) stress the importance of further exploring and specifying these knowledge and skills areas. Taking up their challenge, our focus in this paper is on cognitive skills. We operationalize these skills for interdisciplinary environmental science education and examine how to train students in them through environmental systems analysis. Environmental systems analysis is a scientific field that allows the investigation of environmental issues and possible sustainable solutions. It can be seen as the application of systems approaches to the domain of environmental sciences. Thus, the following questions guide our paper:

1. What are the cognitive interdisciplinary skills that enhance students' ability to understand complex environmental problems and develop sustainable solutions?
2. What can education in environmental systems analysis contribute to training these cognitive skills?

We base our findings on a systematic literature review combined with our own experience in teaching 'cognitive interdisciplinary skills'. We have been involved for more than two decades in developing and teaching environmental science and environmental systems analysis courses and during that time have interacted closely with colleagues all over the world. In this paper we draw on this experience and use a case study from our own educational practice to operationalize and illustrate our literature-based findings. The case study is a Bachelor of Science course in environmental systems analysis at Wageningen University, The Netherlands. Two of the three authors (Fortuin and Kroeze) have been involved in developing and teaching this course. We assessed the reflections of three cohorts of students who have completed this course.

In following sections, we first specify the domain of environmental science education and its characteristics. Secondly, we identify a set of cognitive interdisciplinary skills. Thirdly, we introduce systems approaches in general and assess more specifically what education in environmental systems analysis can contribute to addressing complex problems solving. Finally, we present the case study. Using students' reflections (written as part of their course requirements) we discuss the potentials and limitations of environmental systems analysis education to train students in the cognitive skills identified.

4.2 Characteristics of environmental science education

A widely diverging set of higher education environmental curricula has been developed worldwide over the last four decades. These environmental curricula usually include a broad range of disciplines from natural sciences, social sciences as well as the humanities. Although such curricula draw upon knowledge from various disciplines, they can differ with regard to the key disciplines involved and the relative emphasis on natural sciences, social sciences, or humanities (Maniates and Whissel 2000; Vincent and Focht 2009; Newing 2010). In this paper we focus on environmental science curricula that combine natural and social sciences.

Further characterization of environmental curricula can be based on Vincent and Focht (2009). They identified three distinct, but not opposing curriculum perspectives: (i) '*the Environmental Scientist'*, referring to a curriculum that is anchored within a single discipline such as chemistry or biology; (ii) '*the Environmental Citizen'*, favouring a broad curriculum that includes the natural sciences, social sciences as well as the humanities; and (iii) '*the Environmental Problem Solver'*, aiming to produce environmental professionals who are able to use systems approaches and draw upon insights and tools from various disciplines in order to address complex environmental issues. In this paper we focus on this last category.

It is particularly in this third type of curricula where students need to be educated in dealing with complex problems (i.e. problems characterized by uncertainties, diverging social interests and conflicting views on the nature of the problem and the best ways to solve it). It is not sufficient that these students acquire relevant combinations of disciplinary knowledge and skills. They need to be educated in the ability to analyse and design solutions to environmental problems by integrating knowledge from different disciplines (Newing 2010). Moreover, students need to realize the limitations of science in dealing with environmental problems because most solutions require stakeholder involvement (Fortuin et al. 2011). Students need to know the difference between solving a problem and acquiring new knowledge. They also need to grasp the difference between scientific knowledge, stakeholder knowledge and lay knowledge.

4.3 Cognitive skills required for solving complex problems

As stated above, environmental problems are often complex and not structured according to individual scientific disciplines. Designing sustainable solutions requires a broad set of competencies of the people involved, including cognitive interdisciplinary skills, as a key element for both the analysis of environmental problems and the formulation of solutions (Vincent and Focht 2011). In order to successfully implement the teaching of these cognitive interdisciplinary skills in undergraduate or graduate courses in environmental sciences, they need to be operationalized.

Before doing so, it is important that we define what we mean with cognitive interdisciplinary skills. Cognitive interdisciplinary skills enable a student to appropriately scope the issue or problem under study (Spelt et al. 2009; Vincent and Focht 2011) and "to integrate knowledge and modes of thinking in two or more disciplines or established areas of expertise to produce a cognitive advancement—such as explaining a phenomenon, solving a problem, or creating a product—in ways that would have been impossible or unlikely through single disciplinary means" (Boix Mansilla and Duraising 2007, p219). Cognitive interdisciplinary skills, in our definition, differ from disciplinary knowledge, such as disciplinary theories and research paradigms, and also differ from disciplinary methods, including specific technical or analytical skills. They may however, require specific kinds of knowledge about disciplines, for example insights in the kind of contributions that can be expected for addressing environmental problems. Furthermore, by speaking of *cognitive* interdisciplinary skills, we also distinguish them from communication skills, presentation skills, project management skills, writing skills and other more narrowly defined 'instrumental' skills. These later skills are extremely important in interdisciplinary environmental sciences, but are beyond the scope and analysis of this paper.

Having defined cognitive interdisciplinary skills, the question remains what makes up these skills? Building upon the work of authors already mentioned and others (e.g., Boix Mansilla et al. 2009; Boix Mansilla and Caviola 2010; Van der Lecq et al. 2006) as well as on our own experience in environmental science education, we suggest an operationalization for university level interdisciplinary environmental science education on the basis of three component skills which jointly constitute the competency required for developing sustainable solutions for environmental problems.

First component skills: understanding environmental issues in a holistic way

The first component skill is the ability to understand environmental issues in a holistic way, taking into account the interplay of biophysical and social dynamics. This ability implies that students, when asked to frame an environmental problem, for instance eutrophication of a lake, recognize that this is not merely a matter of pollution or damage to the ecosystem, but that there are likely to be underlying societal causes and effects. Students should be able to identify relations with national or even international policies and markets that stimulate intensive agriculture practices and high inputs of fertilizers around the lake, resulting in nutrients runoff. Potential solutions for an eutrophication problem might not just involve local farmers, but also other local, national and maybe even international stakeholders. Such a broad scope requires the involvement of various disciplines. Knowledge from hydrology, chemistry, and ecology is required to investigate the flow of nutrients and their impacts on flora and fauna in the water, and knowledge from agricultural economics, and policy science is needed to investigate how agricultural markets and policies influence agricultural practices. Disciplinary experts tend to frame problems in a way that it fits their expertise (Brand and Karvonen 2007). This first cognitive skill is the ability to frame environmental problems in a way that allows a more comprehensive insight into all aspects that are relevant to possible solutions of the problem.

Second component skill: identifying, understanding, appraising and connecting disciplinary knowledge

The second component skill is the ability to identify, understand, critically appraise and connect disciplinary theories, methodologies, examples and findings into the integrative frameworks required to analyse environmental problems and to devise possible solutions. This ability is related to '*disciplinary grounding'* and '*integration'* (Boix Mansilla and Caviola 2010; Boix Mansilla et al. 2009). Disciplinary grounding refers to the ability to use disciplinary knowledge (concepts, theories, perspectives, findings and examples) and methods accurately and effectively. The word 'use' is important here and differs from having or accumulating knowledge (Boix Mansilla and Duraising 2007). Disciplinary knowledge in environmental sciences is used as a means to a purpose, i.e. it is used to analyse an environmental problem and develop solutions. Students should be able to assess the potential contributions by particular natural and/or social science disciplines and to indicate ways of involving these disciplines in the investigation of the problem at hand. Integration refers to selecting and connecting disciplinary knowledge into a coherent whole resulting in an advanced understanding of the problem (Boix Mansilla et al. 2009). An integrative framework, such as a conceptual model illustrating a holistic understanding of cause and effect relationships, can facilitate this integration.

It is neither mandatory nor possible for environmental scientists to have in-depth knowledge of all possible and relevant disciplines. More importantly they should have enough understanding of the major relevant disciplines to be able to appraise their contribution to a problem at hand. The environmental problem determines which disciplinary knowledge is needed and how this is to be integrated with other knowledge. Environmental scientists must have sufficient disciplinary knowledge to be able to communicate with disciplinary experts and be aware of the limitations of their own knowledge.

Third component skill: reflecting on the role of science in solving environmental problems

The third component skill is the ability to reflect on the role of disciplinary and interdisciplinary research in solving societal problems. Reflective skills are also needed within the first and second component skill. For instance, in order to integrate various disciplines, students have to be able to reflect on the limitations of a mono-discipline and to recognize methodological and theoretical potentials of other disciplines (Van der Lecq et al. 2006; Boix Mansilla and Duraising 2007). With this third component skill, we refer first of all to the ability to reflect on the position of scientific knowledge within society, on the societal interests that inevitably guide scientific research, and on the differences between natural sciences, social sciences and lay knowledge such as knowledge held by local communities who are directly experiencing the problem or knowledge held by governments who are in charge of administration or funding of the solution to the problem (Dyball et al. 2007).

This reflection is crucial when cooperating with non-scientific stakeholders from local communities or governments. It is different from self-reflection (reflection on one's own behaviour) and cultural reflection (e.g., reflection on group dynamics). Students should be able to reflect on the value of what they know and how they got to know this. Mastering this third component skill helps students to adequately deal with the normative choices, opportunities, compromises, stakes and limitations that are part and parcel of practice-oriented interdisciplinary research. In other words: while the second component skill is about understanding, using and connecting major disciplines, the third component skill is about critically assessing the role of science in society.

4.4 Characteristics of systems approaches

Systems approaches start from the assumption that employing 'systems thinking' and 'systems practice' is a way of gaining a better understanding of the complexity of the real world. There is a rich history behind current systems approaches (see e.g., Olsson 2004; Ison 2008b). Along with the development of computational technologies, systems thinking and practice have developed rapidly over the last decades in various fields, including in environmental sciences.

Characteristic of systems approaches is that the area of interest is considered to be a system, i.e. the whole is taken into account as well as the interactions between the parts. Moreover, a system approach starts from the position that the whole has properties that cannot be known from analysis of the constituent elements in isolation. The emphasis of the analysis in a systems approach, therefore, shifts from a focus on the separate parts to the way they interact (Jantsch 1972). This is in contrast to the usual scientific practice where the focus is generally on a specific part.

A vital aspect of the systems approach is the realization that each system is a simplification of reality and that each system practitioner has his or her own perspective on the system (Tuinstra and Bindabran 2002; Ison 2008b; Ison 2008a). Perspectives, interests and experiences (educational, practical etc.) of a system practitioner determine how a system of interest (object of study) is viewed and how boundaries that demarcate the system under study and the outside environment are set. Thus the system of interest cannot be seen independently from the system practitioner. Realizing this is crucial for systems approaches.

It is important to make a distinction between '*systemic'* and *'systematic'* thinking. We define systems approaches to encompass both. A systemic approach pays particular attention to the whole within clear boundaries and to interconnections, as explained above, whereas a systematic approach is more of a linear, step-by-step procedure to deal with all relevant aspects of the issue at hand. A system practitioner might follow a systematic approach (and in fact often does so), but in systems approaches the prime concern is systemic thinking, i.e. "thinking in terms of wholes" (Ison 2008b, p148).

Systems approaches make use of '*systems theory'* and '*systems methodology'*. Systems theory is a set of interrelated concepts and principles applying to all systems. Examples of characteristic concepts are presented in Table 4.1. Systems methodology is a set of models, methods, and tools including systematic approaches that apply systems thinking and systems theory to the analysis, design, development, and management of complex systems (Banathy 1988). Both systems theory and systems methodology are applied in order to get a better understanding of complex issues.

There is a vast range of systems approaches. The literature on definitions and interpretations of systems approaches is rich and covers a wide range of scientific disciplines and applications. However, an in-depth discussion of this literature is beyond the scope of this article (for overviews and debate see e.g., Olsson 2004; Ison 2008a; Ison 2008b; Jansen 2009). We will take a more pragmatic approach and focus on *what a systems approach does,* and *what it achieves,* rather than *what it is* (Olsson and Sjöstedt 2004, p3). In the following sections, we take up environmental systems analysis as an application of systems approaches to the domain of environmental sciences, and we discuss the possible contributions of education in environmental systems analysis to the training of students in the three component skills we identified earlier.

Table 4.1 Characteristic concepts and principles from systems theory

Systems: An integrated whole whose essential properties arise from the relationships between its parts. These parts are also called: 'elements', or 'agent' or' actors'.

Boundary: The borders of the system, determined by the observer(s). The boundaries demarcate the system under study and its environment.

Environment: That which is outside the system boundary and which affects and is affected by the behaviour of the system (the 'context' for a system of interest). A distinction can be made between an *open* and a *closed* system, which refer to the relationship between the system and its environment.

Feedback: A form of interconnection, present in a wide range of systems. Feedback may be negative (compensatory or balancing) or positive (exaggerating or reinforcing).

Emergent properties: Properties which are revealed at a particular level of organization and which are not possessed by constituent sub-systems. These properties emerge from an assembly of sub-systems.

Hierarchy: Layered structure; the location of a particular system within a continuum of levels of organization. This means that any system is at the same time a sub-system of some wider system and is itself a wider system to its sub-systems.

Networks: An elaboration of the concept of hierarchy which avoids the human projection of 'above' and 'below' and recognizes an assemblage of entities in relationship, e.g., organisms in an ecosystem.

Perspective: A way of experiencing which is shaped by our unique personal and societal histories, where experiencing is a cognitive act.

(Based on Ison 2008b, p141-142; for a longer list of definitions see: Olsson and Sjöstedt 2004 and Ison 2008b)

4.5 Contributions of environmental systems analysis to training in cognitive interdisciplinary skills

Environmental systems analysis aims at improving decision making by providing relevant and structured knowledge on the environmental problem itself, the range of potential responses to the problem and the consequences of these responses (Quade and Miser 1997; Olsson and Sjöstedt 2004). As a scientific field it aims to develop and apply integrative tools, techniques and methodologies to better understand environmental problems from different perspectives, including natural and social sciences, society, economy and technology, as well as to develop sustainable solutions for these problems (Ahlroth et al. 2011).

Our assessment of the potential contributions of education in environmental systems analysis to the development of cognitive interdisciplinary skills is summarized in Tables 4.2 and 4.3. This assessment is based on literature as well as our personal experience in teaching environmental sciences. Table 4.2 presents the possible link between cognitive interdisciplinary skills, the contribution from systems theory and systems methodology and the consequences for environmental systems analysis education. Table 4.3 presents a list of examples of environmental systems analysis tools. As the tables show, education in environmental systems analysis can improve the students' knowledge about integrative tools and techniques and methodologies and their application, but also – to a certain extent – their cognitive interdisciplinary skills.

For the first component skill - the ability to understand (environmental) issues in a holistic way, whilst taking into account the interplay of social and biophysical dynamics - systems approaches have much to offer. By its nature, the strength of a systems approach is that it is supportive in conceptualizing complex issues. Systems theory provides a set of interrelated concepts and principles (Table 4.1) that can be used to describe and structure environmental issues. Furthermore, systems methodology provides integrative models, ranging from conceptual maps to formal system dynamics or agent-based models, that can be used to conceptualize, analyse and evaluate interactions between human systems and Earth systems (see e.g., Grant 1998; Fortuin et al. 2011). These concepts, principles and models provide a language that facilitates communication in interdisciplinary work in environmental sciences (Olsson and Sjöstedt 2004). By using these concepts, principles and models and by applying them to environmental problems, students become aware of the broader context of an environmental problem, the direct and indirect causes, the direct and indirect effects, the connection between local and global issues and the interaction with various societal actors.

Table 4.2 Relation between the cognitive interdisciplinary skills, systems theory and methodology, and implications for environmental systems analysis education

Cognitive interdisciplinary skills	*Contribution from systems theory and methodology*	*Implications for environmental systems analysis education*
The ability to		Students should
1. understand environmental issues in a holistic way, taking into account the interplay of social and biophysical dynamics.	• A set of interrelated concepts and principles (see Table 1) to conceptualize human and Earth systems and their interactions. • Integrative models to quantify and evaluate interactions within and between human systems and Earth systems.	• be exposed to, apply and reflect upon systems concepts and principles (see Table 4.1) as well as integrative models. • develop their own integrative conceptual model to describe an environmental issue and possible solutions, and reflect upon it.
2. connect the analysis of environmental problems and the design of possible solutions with relevant disciplinary knowledge and methodologies.	• Insight in the nature of (sub)systems (e.g., hard, soft, related to which disciplines) • Tools, methods, models and (e.g., systematic) approaches to assist in structuring complex environmental issues (see Table 4.3). • Tools, methods and models to integrate various disciplinary theories, methodologies, examples and findings (see Table 4.3).	• be exposed to, apply, and reflect upon environmental systems analysis tools, methods and models (see e.g., Table4. 3). • be encouraged to identify and connect various disciplinary approaches (disciplinary theories, methodologies, examples or findings) in studying the same environmental problem and possible solution. • apply and reflect upon a systematic approach that is characteristic for environmental systems analysis.
3. reflect on the contribution of scientific research in solving environmental problems.	• The realization that a system of inquiry is defined by the system practitioner. • Heuristic model for meta-reflection.	• reflect on the tools, methods and models applied, e.g., by using the heuristic model (see Fig.4. 1). • reflect on the contribution of various disciplines (theories, methodologies, examples and findings) as well as on integrative approaches (tools, methods and models) to investigate environmental issues.

For the second component skill, we suggest that education in environmental systems analysis is: (i) able to enhance students' ability to *identify* and *connect* disciplinary approaches in integrative frameworks; and (ii) able to enhance *to some extent* the students' ability to *critically appraise* disciplinary approaches in integrative frameworks. Education about systems theory can provide students with insight in the nature of (sub)systems (e.g., technical, biophysical, or social systems). Education about systems tools and methods (see e.g., Table 4.3) can assist students to structure environmental issues (e.g., by applying a systematic approach) and to integrate disciplinary knowledge (e.g., by applying specific tools such as life cycle assessment (LCA) or integrated models such as RAINS (see Box 4.1)). Applying systems tools and methods helps students to realize that there are various disciplinary approaches, each with their own disciplinary perspective that are relevant to study an environmental issue. For a real understanding of disciplinary approaches and for disciplinary grounding, disciplinary education (i.e. education about disciplinary theories, concepts and methodologies) is needed.

The third component skill, i.e. reflection on the roles of scientific (disciplinary and interdisciplinary) research, lay understandings, and societal choices and interests in solving environmental problems is not inherent to systems approaches. A systems approach might facilitate this reflection, but more is needed. Figure 4.1 illustrates a simple heuristic model for reflection on interdisciplinary research (Ison 2008a). The inner part of Figure 4.1 depicts the research practice: a researcher, shaped by a unique history, which has a framework of ideas (F), applies a methodology (M) to a situation (A) in which the research is practiced. This picture enables reflection on the separated elements F, M and A, but also on the connections between F-M-A, for example, how good was the research? In addition, it can be used to take a meta-view on the research practice.

Table 4.3 Overview of how a selection of environmental systems analysis tools typically included in courses on environmental systems analysis at Wageningen University allows for the development of cognitive interdisciplinary skills

Environmental systems analysis tool	*Aim*	*Component Skill*		
		Systemic view	*Integration of disciplinary areas*	*Reflection on the usefulness of systems analyses (science - society) interface*
Conceptual models	To illustrate a common framework to analyse complex systems	Including causes, effects and solutions of an environmental issue.	Social sciences, natural sciences, humanities and/or technology	System boundaries, elements and relations are preferably user-defined
Environmental indicators	To depict environmental trends or evaluate and monitor effects of environmental policies	Can be related to each other in (conceptual) models	Depending on type of indicator all disciplines can contribute	Indicators are preferably user-defined
Scenario Analysis	To describe future developments	Integrative framework; may be qualitative and/or quantitative	Social sciences, natural sciences, humanities, and/or technology	Expectations and worldviews of the user of the analyses may be reflected in scenarios
Life Cycle Assessment	To assess the environmental impacts over the lifetime of a product (or service)	Life-cycle approach; links the social domain with the biophysical	Mainly natural science and technology	System boundaries, and the impact categories included are preferably user-defined
Stakeholder Analysis	To analysis interests, views and opinions of stakeholders	May include an analysis of networks of institutions	Social sciences and humanities	Stakeholders reflect the societal context
Multi Criteria Analysis (MCA)	To facilitate decision making for complex problems on the basis of multiple criteria	Often combined with other tools, such as LCA, indicators or scenario analysis	Social sciences, natural sciences, humanities and/or technology	Subjective valuation of criteria is user-defined.
Cost Effectiveness Analysis	To analyse the costs and effects of environmental measures	Makes a monetary comparison of environmental policy possible	Economics	Monetary evaluation of policies may help to prioritize
Ecosystem services analysis	To analyse the benefits humans derive from ecosystems	Comprehensive overview of ecosystem services can help valuation of these services	Social sciences and natural sciences	User-defined identification and valuation of services
Environmental Impact Assessment	To evaluate the consequences of a specific human activity on the environment	Assessment of all environmental impacts of an activity compared to alternatives	Natural and social sciences	Often performed for specific user groups, and required by law
Integrated assessment (IA) models	To evaluate the environmental and societal consequences of human activities and environmental management	Integration of knowledge on causes, effects and solutions	A variety of natural and social sciences	Effective IA models are typically designed with and used for specific user groups

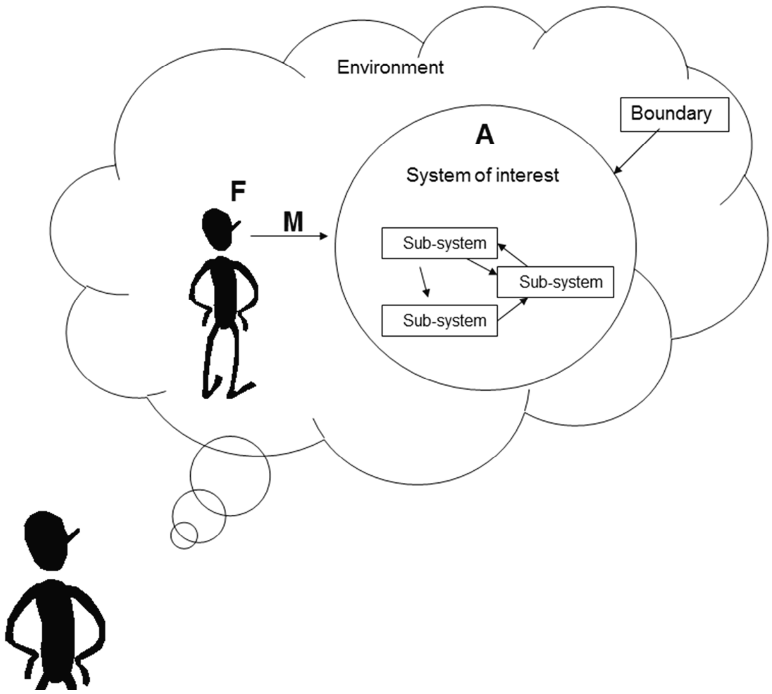

Figure 4.1 Heuristic model for reflection (based on Ison 2008a)

This is illustrated by the second person in the left corner. For a collaborative interdisciplinary project this model could be extended by including more researchers and stakeholders, all with their own framework who study a particular area. In this way the picture becomes a heuristic model for meta-reflection on interdisciplinary research.

Reflecting on the research practice, can make students aware that they themselves use a particular framework and methodology and that other people involved may use different frameworks and methodologies. This reflection might help them to relate their own approach to others and increase their epistemological and societal awareness (Van der Lecq et al. 2006). How to stimulate such reflexivity, however, is a complex issue, and the heuristic model of Figure 4.1 can only be a first step. An in-depth discussion of this issue goes beyond the scope of this paper. Here, we just note that exposing students to multiple perspectives in practice provides a concrete basis for reflection, and insights from cultural studies and philosophy of sciences, among others, can help to sensitize and articulate their thinking.

4.6 Education in environmental systems analysis: a BSc course

4.6.1 Introduction

Since 2000, courses in environmental systems analysis have been an essential part of the Bachelor of Science (BSc) and Master of Science (MSc) environmental science curricula at Wageningen University. Over the past twelve years these courses have evolved and characteristic course elements can be distinguished (see Box 4.1, Figure 4.2 and Table 4.3).

In this paper we use a BSc course in environmental systems analysis to operationalize the contribution of systems analysis to the development of cognitive skills. We first characterize the course and then use reflections of three cohorts of students to illustrate the resulting student perspectives on environmental systems analysis.

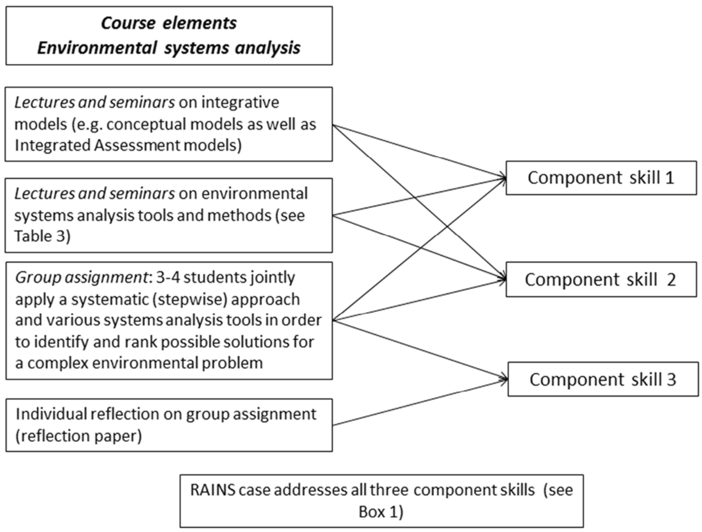

Figure 4.2 Elements of the BSc course in environmental systems analysis

The BSc course introduces students to environmental systems analysis. The course starts with introducing the role of environmental systems analysis in supporting decision making on complex environmental problems and introduces a systematic approach that can be followed to analyse complex environmental problems and their possible solutions. This approach is based on the method described by Findeisen and Quade (1997). It comprises the following six steps that are performed in an iterative way: (1) formulating the problem; (2) identifying, designing and screening possible alternatives; (3) forecasting future contexts or states of the world; (4) building and using models for predicting the consequences; (5) comparing and ranking the alternatives; and (6) communicating the results. Students learn about this approach and practice it in seminars and group exercises. In various lectures analytical tools and techniques that are characteristic of environmental systems analysis are presented (see Table 4.3). Special lectures are dedicated to stakeholder participation and the importance of communication in environmental systems analysis. The importance of identifying the intended end user(s) of the study is stressed, as is the importance of involving the user(s) in the formulation of the problem, the identification of potential solutions, and the evaluation of different options to solve the problem.

Students are required to apply the theory from the lectures in a group assignment, using the systematic systems analysis approach as well as a selection of the tools to a complex environmental problem of their own choice (e.g., sustainability of bioethanol; eutrophication of the Baltic Sea; improving water quality in the Huai River Basin) and present their findings in a collaboratively written scientific report. In the context of this BSc course it is not possible for students to really contact a user, but we encourage students to reflect on the potential role of the users of the results in a full systems analysis. The group assignment is based on literature study and group discussions. At the end of the course the students are asked to reflect individually on this assignment by writing a short paper of about 1000 words. These reflection papers form the basis of our analysis of student responses presented below.

4.6.2 Results of the BSc students' reflection

Reflection papers of three cohorts of BSc students have been analysed (total n=58). It should be noted that the students groups of the year 2007 (n =16) and 2008 (n= 20) were more heterogeneous (as defined by study areas as well as nationality) than the group of 2010 (n= 22) (see Table 4.4). Another variation was that in 2007 and 2008 students received a written assignment in which they were asked to reflect upon what they learned from the group assignment and upon the value of systems analysis in dealing with a complex environmental problem. At least half of the reflection in the resulting papers dealt with the group process, such as the interaction between group members, the division of tasks and the decision-making procedure. In 2010 the reflection assignment was introduced in a short plenary session and students were instructed to focus their reflection on environmental systems analysis approaches and tools, and less on group dynamics of doing the assignment. Below we present issues that emerged from the reflection papers. Issues are grouped according to the three cognitive skills defined earlier, and identify some additional issues. We illustrate our results with quotes from students. The numbers in square brackets refer to the year the course was given and a student identifier.

Table 4.4 Overview of RAINS course elements that are included in Wageningen MSc/BSc systems analysis programs and contribute to the development of cognitive interdisciplinary skills

	Cognitive skills		
RAINS course element	Understand (environmental) issues in a holistic way	Connect disciplinary knowledge in integrative frameworks	Reflect on meta-level
Introductory lectures	Students learn about the causes, effects and solutions of transboundary problems, and how to model these in an integrated way	Students are introduced in natural and social science aspects of transboundary air pollution problems	-
Role play	Students experience the complexity of negotiating environmental policy	-	After the role play, students reflect on the decisions they made as a person and as a group
Hands-on RAINS training	Students learn (hands-on) how complex environmental problems can be modelled for decision support	Students learn how emissions of pollutants, atmospheric transport, environmental impacts, cleaner technologies and their costs can be modelled in an integrated way	-
Lecture on the use of RAINS	Students hear about the role of information and models in solving complex environmental problems	-	-
Reflection	Students discuss the strengths and weaknesses of the RAINS model as an integrated model	-	Students discuss the strengths and weaknesses of the RAINS model as a decision supporting tool

Box 4.1: RAINS case

The GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model , and its predecessor the RAINS model have been developed at the International Institute for Applied Systems Analysis (http://www.iiasa.ac.at/rains/gains/) (Amann M. et al. 2004). RAINS is an Integrated Assessment (IA) model that has been used extensively as a decision support tool during international negotiations on air pollution control in Europe (Tuinstra, et al. 1999; Tuinstra et al. 2006). RAINS models transboundary air pollution problems in Europe (acidification, eutrophication and tropospheric ozone) in an integrated way, taking account of the most important causes of the problems (emissions of air pollutants), atmospheric transport (from country to grid), the environmental impact in terms of critical load exceedance, emission reduction options, and their costs (i.e. country-specific cost curves).

RAINS has been used since the early 1990s in BSc and MSc courses in environmental systems analysis at Wageningen University. We use a version of the model that was used during the negotiations for the second sulfur protocol in Europe. The RAINS teaching typically consists of five different course elements: (1) Introductory lectures on transboundary air pollution problems and on the structure of the RAINS model to learn the details of the IA model, and how causes, effects and solutions are integrated in the model, (2) A role play based on the actual international negotiations on reducing sulfur emissions, in which students experience what stakeholders feel and how their perspectives result in opinions and actions; to learn about the importance of agreeing on numbers, (3) Hands-on RAINS training, to gain experience in running an IA model, to learn how the model integrates causes, effects and solutions, and to learn about the strengths and weaknesses of the model, (4) Lectures on use of RAINS in negotiations: what happened really during the negotiations, and since then, and (5) Reflection: a plenary discussion on the strengths and weaknesses of the RAINS model, focusing on the question why this model has been so successful as a decision supporting tool.

One of the reasons why we use RAINS is that we consider it a good example of an environmental systems analysis study. The model combines different analytical tools, including environmental indicators, scenario analysis, cost effectiveness and analysis, optimization analysis.

The RAINS course elements contribute to the development of three cognitive skills of students (Table 4.4). Students learn to understand air pollution in a holistic way by all course elements. RAINS is a clear example of how to approach a complex problem in a structured and comprehensive manner. In addition, they gain disciplinary knowledge on air pollution by attending the lectures and during the hands-on training. Disciplinary knowledge ranges from atmospheric chemistry to the economic aspects of environmental measures. Reflecting on a meta-level is trained in particular in the reflection exercise that is done after the other course elements have taken place. Students are asked to critically discuss the strengths and weaknesses of the model, and to think about why the model has been so successful, given the many uncertainties that are still there.

Understanding environmental issues in a holistic way

As part of their group assignment, students are required to design a conceptual model or causal diagram of a complex environmental problem and indicate possible causes, effects and solutions. In doing so they must describe the interplay between social and biophysical dynamics of an environmental issue in a holistic way (see first component skill). Students are asked do this in groups of 4-6 students so that they are exposed to different perspectives and to the various ways in which the same problem can be depicted. We then consider causal diagrams as the basis of further analysis.

This assignment was very instructive for students, because they gained insight into the 'bigger picture' and realized that they had to set boundaries. As one student expressed:

> I consider the causal diagram as a very important tool. It gives structure and overview and helps to demarcate your problem. This helps you during the whole environmental systems analysis [2010-13].

Table 4.4 Characteristics of the participants of the courses involved in the study

BSc participants in year 2007

- 16 BSc participants in 2007; all 16 handed in a reflection paper
- 11 male, 5 female
- 16 BSc students Environmental Sciences, 1 BSc student Economics and Policy
- 11 Dutch, 4 Chinese

BSc participants in year 2008

- 21 BSc participants in 2008; 20 handed in reflection paper
- 11 male, 9 female
- 11 BSc students Environmental Sciences, 3 BSc student Economics and Policy 1 Forest & Nature Conservation, 5 other
- 14 Dutch, 2 Chinese, 1 Belgian, 1 Polish, 1 Czech, 1 German

BSc participants in year 2010

- 24 students followed the course; 22 handed in a reflection paper
- 11 male, 11 female
- 22 BSc students Environmental Sciences
- 21 Dutch, 1 German

The majority of the students who took the BSc course Introduction to Environmental Systems Analysis was Dutch and followed a BSc in Environmental Sciences. Students from other BSc programs as well as international students were enrolled as well. As a result it was possible to make teams that were diverse in educational, as well as cultural background.

Almost all students mentioned in their reflection papers that they realized that environmental problems are often complex and that multi- (or inter-) disciplinary and multi-stakeholder approaches are required to solve them. They valued the systematic approach introduced in the course as valid method to obtain a better understanding of a problem as well as a way to develop solutions. A student who analysed pollution in the Huai river basin in China wrote:

> Through the complex societal context of the problem it is impossible to search merely for technological solutions. The system analytical approach gave us the opportunity to investigate and elucidate underlying motives [2007-11].

Another student wrote:

> I think systems analysis can be a very useful procedure when dealing with a complex environmental problem in general. It has the potential to create broad and detailed understanding of a problem, of its causes and effects [2008-19].

Systematic versus systemic approaches

Most of the students were happy that environmental systems analysis provided them with a structured and clear way to cope with an overwhelmingly complex problem. Some students even appeared relieved that there was a systematic approach that helped them to navigate this complexity, as the following quotes illustrate:

> Because there are so many factors, actors, stakeholders involved in environmental problems it is very difficult to make a good analysis [2008-11].

> This assignment showed me how a complex societal problem can be clarified … where choices have to be made between social, technical and practical problems and questions, a systematic analytical approach can give a solution [2007-1].

A few students experienced the systematic (six-step) approach that was introduced to them as too rigid, thus limiting their creativity:

> We had to stick to the six-steps that were introduced in the lectures. I had the feeling my hand and feet were bound [2007-2].

A few students realized that this approach had to be applied in a flexible, iterative way and only fewer still realized the importance of iteration within these six-steps:

> I interpreted the tools in first instance more as a recipe book. In hindsight this seemed not to be the right approach. We should have realized that earlier” [2010-13].

> Also the idea that an environmental systems analysis is not a fixed procedure, but a dynamic process in which different techniques and tools can be used to reach a certain goal was something I did not think about before [2010-9].

Tension between detailed knowledge and gaining a general overview

Several students mentioned that while doing the systems analysis and applying the analytical tools they faced limitations in available time and data. Sometimes they felt frustrated by this, although they realized that they participated in a course and the main aim was to learn about environmental systems analysis. As a student wrote:

> I think we did a good analysis considering the available data. We got a lot more understanding of the problem, but I doubt the reliability of our environmental systems analysis because of the lack of time and the limited amount of data [2008-18].

Another student learned that it is not possible and necessary to know all the details:

> This project has taught me to be satisfied with a more general overview of the problem [2008-19].

Yet another student learned that environmental systems analysis requires a lot of time and effort:

> If we were to perform a real systems analysis we would have needed a lot more time, and a lot more knowledge and skills [2007-8].

Identifying, understanding and appraising disciplinary knowledge

By applying analytical tools students experienced the process of integrating various disciplines which is an important aspect of the second cognitive skill. For some students this was an eye opener:

> Before the start of this course I thought I did not like to work on something that is not touchable, concrete and practical. … social sciences and politics were not my field … [In this course] I experienced that a large part of these complex environmental problems is made up of human opinions, interests and behaviour. Something has to be done in this field before actions and measures are taken. I think this is the best way: it is necessary to analyse the problem as complete as possible, with different tools and from different angles and disciplines. I also think it is a very good method because it allows and even invites for the involvement of stakeholders in many parts. ... The topic of our group work was a very good example of a very complex environmental problem. The complexity lays not in the natural sciences part, but mainly in the conflicting interests of people and the organization of politics [2007-15].

Another one writes:

> My opinion on the value of system analysis tools has changed considerably through this project. At first, I thought that using system analysis tools was hardly ever needed, even in the more complex problems. This mental image has changed completely, since I found that relying on tools in projects with complex environmental problems like the one we faced is needed, not optional [2010-11].

Especially in heterogeneous groups students experienced that collaborators that had a different educational background to their own can bring in new perspectives and insights. Many students judged this as positive, because they acknowledged that they can learn from each other. A student in Economics and Policy mentioned:

> Working with environmental scientists certainly expanded my understanding of Environmental Systems Analysis much further than if I had worked on my own [2008-13].

A student in environmental sciences from 2008 explained that it was the first time she worked together with students from other study programs:

> In theory I knew that it is good to work together with people from different disciplines, because you learn to perceive a problem from different angles …. In this course I experienced that we used different perspectives. At first I experienced this when we made the causal diagram [2008-12].

A student in Economics and Policy considered the scope of the course very focused on studying environmental impacts. He wrote: “Although the environmental systems analysis is an integrated analysis, I think the integration should go further” [2008-14]. In his opinion economics should be included more, although he realized that choices have to be made, because “in six weeks it is not possible to do everything”. An environmental science student realized the importance of a multi -disciplinary approach:

> I consider it very important to look at a problem from various angles and perspectives. As said in the beginning of the course, it can be beneficial to look at the whole system. I think that if people with the required expertise work together on a complex problem and look at it from different perspectives, broad insight into the issue can be obtained, which can then support the development of a sustainable solution [2008-19].

Reflecting on the role of science in solving environmental problems

The quality of the reflection papers differed considerably, but it was obvious that for the majority of the students it was very difficult to reflect on the systems analysis approach. Most of them hardly touched upon the role of science in societal issues. As part of the group assignment students had to identify a decision maker (the person or organizations for whom they performed the systems analysis) as well as relevant stakeholders, and describe the perspectives of these stakeholders on the selected problem and possible solutions. For the students, this was a theoretical exercise and mostly the perspectives of the stakeholders were depicted one-dimensionally. Although they realized that stakeholders' input in a systems analysis was important, it was difficult for these students to place themselves in the stakeholders' position. A tool that seemed to be instructive in teaching various perspectives was the multi-criteria analysis (MCA): many students applied MCA by evaluating and ranking several solutions for a problem, using a number of criteria derived from different (stakeholder) perspectives. Students realized that the selection of criteria - and thus which solution turned out to be the best - depended on the perspective taken: "With the multi-criteria analysis it was easier to explain different perspectives, and be able to evaluate what might be a good solution" [2010-16]. For some students this realization was disturbing, because it was considered not scientific.

Learning by doing

Almost all students appreciated the practical approach of the group assignment. They realized that 'learning by doing' was the only way to really understand the systematic approach and the application of systems analysis tools. The following quotes illustrate this:

> I liked the combination of lectures and group work of this course because we first received the theory about the different tools and in our group work we could immediately apply them. In this way we could find out by ourselves what the strengths of a certain tool are but also what are its limitations [2008-17].
>
> Using the [systems analysis] procedure yourself as part of this assignment gave much more insight in how it is actually used, even though what we did was not an actual comprehensive systems analysis. [The] same goes for the tools used. If I would have just been taught how to apply the tools, but never would have gotten to apply them I would not have learned as much [2007-8].

Learning through interaction

Students recognized that they also learned from interactions with peers: "It is not only because you have people with different opinions, that group work is important, also because these people have different capacities" [2008-12]. This learning through interaction was clearly affected by the group composition. In 2010 – when only students in environmental sciences participated and almost all were Dutch - only two out of 22 students mentioned the integration of various perspectives in their reflection papers, whereas in 2007 and 2008 when the composition of the groups were more heterogeneous, 12 out of 16 and 13 out of 20 respectively commented on this issue. A student in 2007 who happened to participate in a homogeneous team (all Dutch, all environmental sciences) felt she lacked this diversity:

> Our whole group was Dutch. I think this was a pity. Of course, it was easy, because we did not have any difficulties with understanding each other, but I think it would have been instructive to work together with foreigners who often have another way of working [2007-4].

Although in general working in a heterogeneous group was judged positively, students also found it was complicated. Two students mentioned that they acknowledged the value of the different perspectives, but this diverse input was not reflected in the end product of the group work, because the majority of the work was done by the two Dutch students in the group. One wrote:

> I learned interesting issues from the cultures of my foreign group members, but the final report is unfortunately mainly the product of my Dutch group member and me [2008-9].

4.5 Discussion and conclusions

We intended, firstly, to operationalize cognitive skills that are important in developing sustainable solutions for complex environmental problems and, secondly, to examine the contribution of environmental systems analysis in training students in these skills. In this paper we identify three components of cognitive interdisciplinary skills: (1) the ability to understand environmental issues in a holistic way, taking into account the interplay of social and biophysical dynamics; (2) the ability to identify, understand, critically appraise and connect disciplinary theories, methodologies, examples and findings in the integrative frameworks needed to analyse environmental problems and design possible solutions; and (3) the ability to reflect on the role of disciplinary and interdisciplinary research in solving societal problems. We show that education in environmental systems analysis has much to offer to the first and second skills and can to a limited extent contribute to the training of the third skill. Environmental systems analysis provides tools, methods and models that help to conceptualize and frame an environmental issue in a holistic way and to connect and integrate disciplinary knowledge and methods. Our analysis of the students' reflection comments shows that BSc students who followed an introductory course in environmental systems analysis acknowledged this value. Clearly, for disciplinary grounding (required for the second skill) disciplinary education remains crucial. Students need to have sufficient disciplinary knowledge to be able to appraise its contribution to a specific environmental problem. There is no unequivocal answer to the question how far this disciplinary education should go. Some students realized there is a clear tension between having a general overview and detailed knowledge. This tension is characteristic of the systems practice (Hordijk 1991).

There was a great variety in what the BSc students learned from environmental systems analysis, but two main challenges became apparent. The first major challenge is how to stimulate students to move beyond following a *systematic* approach towards having a *systemic* view. There is a real danger that education in systems analysis results in teaching a systematic approach, rather than a systemic approach, in particular when the minds of the students are not yet ready for it (Bawden and Packham 1998; Bawden 2005). Indeed, many BSc students had difficulty in moving beyond the level of merely applying systems tools and techniques in a systematic (i.e. recipe-like) way. The students appreciated the systematic approaches offered by systems analysis, but experienced difficulties in using them in a flexible and iterative way. For real systemic awareness, however, students have to come to the realization that various disciplines use their own specific methodologies to acquire knowledge. Students need some epistemological awareness and flexibility. Therefore disciplinary education, but more importantly reflection on concepts, theories and methodologies is essential (Van der Lecq et al. 2006).

The second major challenge is how to train students to be *reflexive*. Reflection on the research practice from a meta-level turns out to be very challenging for BSc students. These students have no difficulty with reflecting on the group processes and their role in a group assignment, but reflecting on the role of systems analysis and the role of science in solving complex societal problems is more complicated. Students need support in developing the skills to ‘reflect’ (Benammar 2005). Systems analysis might support this by making students aware that a system under study always represents a simplified model and a specific perspective, but more is needed. In this respect, we have noted that concrete experiences in ‘learning by doing’ and ‘learning by interaction’ can inspire reflection, and insights from cultural studies and philosophy may help to sensitize and articulate students’ thinking. Our analysis shows that these strategies are valuable in training cognitive interdisciplinary skills.

It is only by applying a systems analysis procedures and systems analytical tools that students really get the opportunity to grasp the complexity of environmental issues. By jointly conceptualizing a complex problem, and applying systems tools students become aware that they need to make several decisions, and that there is not one way of doing this. Interaction with students in particular when these students have another disciplinary or cultural background than their own accelerates this realization. Being confronted with a diversity of perspectives can be a catalyst and enhances the development of skills needed to deal with complex environmental problems (Dyball et al. 2007; Fortuin and Bush 2010).

Because mastering cognitive interdisciplinary skills is a long-term process and requires continuous attention (Van der Lecq et al. 2006; Newing 2010), we advocate starting training students in these skills at BSc level and we have demonstrated that it is possible to do so through education in environmental systems analysis. When learning-by-doing and learning-through-interaction strategies are applied, other skills that are important for future environmental scientists such as communication skills, presentation skills, project management skills and writing skills can also be developed.

5 Teaching and learning reflexive skills in interdisciplinary and trans-disciplinary research: a framework and its application in environmental science education

Abstract

A crucial skill for researchers in interdisciplinary and transdisciplinary environmental projects is the ability to be reflexive about knowledge and knowledge production. Few studies exist on the operationalization of reflexive skills and teaching and learning strategies that help students master these skills. This research aims to contribute in this direction. We distinguished two components of reflexive skills: (i) assessing the relative contributions of scientific disciplines and non-academic knowledge in addressing environmental issues; (ii) assessing the role of norms and values in research. We developed a framework for teaching and learning reflexive skills and evaluated this framework within a quasi-experimental educational setting involving three groups of thirty students. Students' reflexive skills were assessed quantitatively using a pre- and post-test questionnaire. Moreover, students' reflection papers were analysed to get a better understanding of their perspectives on the teaching and learning framework. We show that it is possible to train students in reflexive skills, but it requires a well-designed learning setting.

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5.1 Introduction

A plurality of university level environmental degree programs have been developed worldwide (see e.g., Vincent and Focht 2011; Bursztyn and Drummond 2013). These programs aim to educate graduates who are able to address complex environmental problems, such as biodiversity loss, climate change or water shortage. Developing sustainable solutions for these problems requires interdisciplinary or even transdisciplinary research. In interdisciplinary research, intensive interaction among disciplines results in integrating data, methods, tools, concepts, and theories; sometimes new methods, concepts, or theories are created (Godemann 2008; Feng 2011). More recently transdisciplinary approaches are promoted to deal with complex societal problems and to attain a more sustainable world. In transdisciplinary research, boundaries between academia and society are crossed. Academic knowledge from various disciplines and non-academic knowledge is integrated and new knowledge is produced jointly by scientists and other stakeholders. Collaboration and mutual learning among academic and non-academic stakeholders are key features of a transdisciplinary approach (Godemann 2008; Polk and Knutsson 2008).

Researchers involved in interdisciplinary and transdisciplinary projects require specific skills. A crucial skill is the ability to reflect not only on the problem and its solutions, but also on the process of knowledge production itself. The concept of reflexive skills in this article refers to the latter. With reflexive skills -as a subcomponent of interdisciplinary and transdisciplinary skills- we mean the ability of researchers to question the different sorts of knowledge used, to recognize the epistemological and normative aspects involved, and to reflect on their own and others' roles in these knowledge processes. Reflexive skills, therefore, are related to what Miller et al. (2008) call the 'internal reflexivity' of interdisciplinary and transdisciplinary research (for a further elaboration on reflexive skills, see section 5.2).

Many authors highlight the importance of such reflexive skills in interdisciplinary and transdisciplinary environmental research and education (e.g., Miller et al. 2008; Godemann 2008; Jahn et al. 2012; Kueffer et al. 2012). Existing literature, however, provides little specific guidance on teaching and learning reflexivity. It is clear from literature that reflexivity, in the sense of this article, is difficult to learn, particularly when it comes on top of the many other challenges posed by interdisciplinary and transdisciplinary environmental research (Vincent and Focht 2011; Godemann 2008; Feng 2011). Research shows that students experience difficulty in reflecting on the differences between scientific knowledge and lay or experiential knowledge and on interests, norms and values that might influence scientific research (Fortuin et al. 2013). Reflexivity, in the words of Godemann (2008: 638) 'does not arise all by itself' but should be trained in academic education.

Much literature exists on how to facilitate interdisciplinary and transdisciplinary learning processes, for example by articulating mental models (Godemann 2008; Fortuin et al. 2011), by an active engagement of teachers in stimulating communication of uncertainties and reflection on dominant ways of thinking (Feng 2011; Wagner et al. 2013), by mixing students with various cultural and disciplinary backgrounds in research groups, and by bringing students in contact with real-world problems and stakeholders (Steiner and Posch 2006; Scholz et al. 2006; Fortuin and Bush 2010). Most of this literature, however, presents teaching and learning strategies for interdisciplinary and transdisciplinary research skills in general. In this research, we aimed at developing and evaluating strategies for reflexive skills specifically.

Our research consisted of three main steps. Building on existing literature, we first developed a conceptual framework for operationalizing reflexive skills and a strategy to teach and learn these skills. Then, we applied this framework within a quasi-experimental educational setting of three groups of students doing transdisciplinary research projects in parallel. In the third step, we assessed the learning outcomes of these projects in two different ways: (1) with a quantitative assessment based on surveys before and after the projects, in order to assess the effectivity of the teaching and learning strategy and to get an indication of the relative importance of its different components, and (2) with a qualitative assessment based on a content analysis of students' reflection reports, in order to get a better understanding of the outcomes from the students' perspectives. The research questions guiding the research are:

1. What are key operational components of reflexive skills –as a subcomponent of interdisciplinary and transdisciplinary skills– and what are key elements of a teaching and learning strategy?

2. To what extent do students' reflexive skills improve after successful completion of a course in which this strategy is applied, and what is the influence of different strategy elements?
3. What evidence of improvement of reflexive skills is found in students' evaluation of the learning process, and to what extent does the operational framework we developed resonate with their perspectives on the learning process?

In the rest of this article, we will present our conceptual framework (sections 5.2 and 5.3); explicate the quasi-experimental research design and methods used (section 5.4); report on the quantitative assessment and present the main findings from the students' reflection reports (section 5.5); and then end with discussion and conclusions.

5.2 Reflexive skills in interdisciplinary and transdisciplinary research

Reflection is part of any academic research. Researchers reflect on their research questions, choice of methods, and interpretation of results. In this article, as we mentioned in the introduction, reflexive skills refer to another sort of reflection, one that critically examines the epistemological principles and normative assumptions underlying the scientific theories and methods used, as well as the status and role of scientific knowledge amidst other values and forms of knowing. Reflection of this nature is less common (Ison 2008a). Especially researchers from the same discipline share fundamental assumptions and values. They share a world view (including one or more theoretical frameworks), language (including a specific jargon), and disciplinary concepts and methods for acquiring and validating knowledge. This shared epistemological perspective is hardly discussed and, in fact, there is often no need to do so in a disciplinary context (Eigenbrode et al. 2007). This is different for interdisciplinary and transdisciplinary research, where reflection on the knowledge process itself is needed for several reasons.

To start with, in interdisciplinary and transdisciplinary projects, researchers with different epistemologies work together. Ignoring that individual epistemologies differ and that multiple epistemologies are valuable for interdisciplinary and transdisciplinary research, might obstruct successful collaboration (Jahn et al. 2012). By reflecting on the differences between disciplines, researchers become aware of disciplinary characteristics, and collaboration can improve (Godemann 2008; Eigenbrode et al. 2007).

Moreover, researchers in the environmental domain often deal rather directly with 'real-world' environmental problems. Environmental issues are characterized by diverging social interests and conflicting views on the nature of the problem and the best solutions. Scientific knowledge alone is often insufficient to address such problems; most sustainable solutions also require other knowledge and mutual learning between academic and non-academic stakeholders (Lang et al. 2012). Non-scientific forms of knowledge (e.g., commonly shared lay knowledge, experiential knowledge, traditional indigenous knowledge) differ from scientific knowledge. They differ in their foundations, their epistemological status and the roles they play in addressing environmental problems. To navigate effectively, researchers need to reflect on these differences between scientific knowledge and other forms of knowing. (Polk and Knutsson 2008; Scholz 2011, Chapter 15).

For similar reasons, researchers in the environmental domain also need to be aware of the norms and values that enter research when 'real-world problems' are addressed. A crucial difference between research aimed at designing sustainable solutions or prescriptive scientific research and descriptive scientific research (i.e. describing and explaining what exists) is that in the former, norms and values are explicitly incorporated. In order to effectively contribute to societal needs, researchers need to be aware of how, which and whose norms and values are at work in the transformation of the societal problem to a researchable problem, the formulation of the research questions, the production of new knowledge and the integration of knowledge (De Groot 1986; Polk and Knutsson 2008; Jahn et al. 2012; Miller et al. 2014).

Reflexive skills enable a person to question processes of knowledge creation and to examine how personal and epistemological influences are interwoven in the research (Smith 2011). This reflection can be done on different levels: (a) a general level (e.g., science in general or an environmental problem in general); (b) the level of a specific project; and (c) the individual level (i.e. one's own position and contribution in terms of scientific and other knowledge, as well as interests, norms, and values in addressing a problem). All three levels are relevant for interdisciplinary and transdisciplinary research.

In sum, two components of interdisciplinary and transdisciplinary reflexive skills characteristic for environmental research can be distinguished:

(i) The ability to identify, differentiate and evaluate the contribution of relevant scientific disciplines as well as the contribution of non-academic knowledge to address a societal (i.e. environmental) problem;
(ii) The ability to identify, differentiate and evaluate the inclusion of norms, values and interests into a research process that addresses a societal problem, and thus into the design of strategies, technologies or scenarios that address this problem.

5.3 A framework for teaching and learning of reflexive skills

In his paper on experiential learning and reflexivity in contemporary modernity, Dyke (2009) presents an 'enabling framework for reflexive learning'. He argues that 'the advancement of learning in reflexive modernity can be promoted by nurturing learning from experience that includes elements of practice, critical reflection, knowledge, interaction and engagement with others' (Dyke 2009, p289). While our article's context and domain of application differ substantially from that of Dyke's, the four elements emphasized in his framework – (1) theory, (2) experience, (3) reflection and (4) interaction with others – formed a useful starting point for our framework.

In the context of this research, *theory* specifically refers to theories relevant to reflexive practice in interdisciplinary and transdisciplinary research. It comprises understandings of the nature of scientific disciplines, fundamentals of science, the characteristics of interdisciplinary and transdisciplinary research (Van der Lecq et al. 2006) challenges of science or scientists to address environmental issues, differences in logic between scientific knowledge and experiential knowledge, and the introduction of norms and values in research. Theory also comprises understanding the importance of reflexive skills in problem-oriented research. A useful model within this variegated body of theory is the one of Jahn (2008), further developed by Lang et al. (2012). This model depicts transdisciplinary research processes and clarifies the differences between societal practice and scientific practice, and the various stages (e.g., problem framing and knowledge integration) of a research process that starts from a real-life issue (see e.g., Godemann 2008; Bergmann et al. 2012). Such a model also supports and stimulates reflection (Fortuin et al. 2011) because it provides teachers and students a tool (i) to explain the difference between societal problem-solving and doing scientific research; (ii) to explain and analyse characteristic stages of transdisciplinary research processes and to discuss basic methodological implications (e.g., problem framing, producing knowledge and integrating and applying knowledge); and (iii) to identify and explain normative aspects in the transdisciplinary research process.

For teaching and learning of reflexive skills, theory alone is not sufficient. Students should experience the complexity of adapting theoretical and research-based knowledge to fit realistic circumstances. They should learn to critically assess the theory and discuss it with others. Experiencing the struggle to integrate theory and practice is perhaps even more important than theoretical understanding (Thompson and Pascal 2012). Thus, the second element of our framework is *experience* (or practice). In the context of this article, it implies that students address a real-world environmental problem (i.e. a concrete societal problem experienced by societal actors). Education consisting of academic assignments or case studies discounts this experience. To gather the sort of experience intended by our framework, students need to engage with actors outside academia. They should investigate and try to solve an environmental problem by facing the differences in norms and values held by the societal actors and by themselves. They need to experience the challenges of applying disciplinary and interdisciplinary methods as well as techniques and procedures to integrate solution-oriented knowledge.

Theory and practice need to be combined with *reflection* (Thompson and Pascal 2012). In describing this third element, we should start by observing that, generally spoken, this is what reflexive skills are all about. Reflection enables students to look from a critical 'meta-perspective' (Smith 2011) to their learning experiences in different situations and contexts. In this article, as we explained above, reflection is directed at the research process, the role of science and the role of norms and values in addressing a societal problem.

Such reflection easily remains superficial and restricted to a moment to pause and think without any analysis or without drawing out learning or new knowledge from the experience (Thompson and Pascal 2012). The element of reflection, as operationalized in our framework, refers to explicit processes in which students are stimulated and supported to reflect critically on their experiences, in confrontation with other experiences and with theory, for example, in reflection assignments and through scaffolding by supervisors.

The last element is the social context of learning and the interaction with *others*. Obviously, others are a crucial element in any learning process, as stated by Dyke: ‘What people say and how they interact with each other, their conversations, dialogue and shared practice, shapes perception and interpretation’ (Dyke 2009, p300). In our framework, this element is operationalized as close interaction and debate among those involved in a particular course or project (including in particular the students teaming up in the research, but also teachers and other academic and non-academic stakeholders). Discursive confrontation with views and practices of others can be a powerful stimulant for reflection, particularly if education is designed in such a way that intensive interaction between persons from different disciplines and cultural backgrounds, and between researchers and societal stakeholders is part and parcel of the research process.

After Dyke (2009), the core elements of teaching and learning of reflexive skills can be represented as a tetrahedron (Figure 5.1) illustrating the interdependence of these four elements. Training students in reflexive skills does not follow a linear path or sequential phases. Instead, the learning activity should be flexible and student centred. The learning is influenced by the interaction of all four elements and a student should be enabled and stimulated “to move back and forth between any of the elements in any particular order” (Dyke 2009, p306).

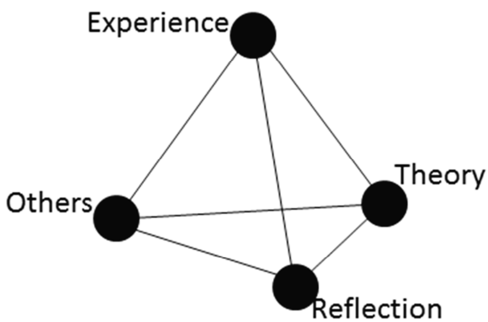

Figure 5.1 Core elements of teaching and learning of reflexive skills (based on Dyke 2009)

5.4 Method

5.4.1 Study context and participants

In order to investigate whether our framework indeed allows for developing reflexive skills we applied it in an existing course '*European Workshop in Environmental Science and Management* (EUW)' for Master of Science (MSc) students in the field of environmental science and natural resource management. In this EUW course a group of thirty MSc students accomplish a realistic consultancy project through a well-structured, collaborative transdisciplinary research approach in an intercultural setting. Students are expected to use scientific knowledge and methods to address a real-life issue for a non-academic commissioner. They collect data through interviews with local stakeholders, a survey and field observations and integrate all data and analysis into one concise report. The eight weeks full-time course is divided into the following phases: (1) problem orientation and problem framing in close collaboration with the commissioner; (2) developing the methodology, including data collection methods; (3) data collection in the field; (4) data analysis; (5) reporting; and (6) reflection. Throughout the course students work in different subgroups: field-work teams or geo-groups investigating a particular geographical area (e.g., a district in a city or small municipality in a region), and disciplinary or expert groups. By switching groups students are able to recognize and deepen their disciplinary knowledge and skills, but are also forced to cross disciplinary boundaries. Moreover, working in different subgroups enables intensive interaction among all thirty students involved. Two weeks of field work provide the students an opportunity to experience the 'complexity of reality' and to interact with the commissioner and local stakeholders. It provides students a context in which they can integrate theoretical knowledge, transcend disciplinary knowledge and combine and connect findings. Furthermore, working and living abroad for two weeks provide plenty of opportunities for discussions, reflection and amazements on the available diversity of customs, approaches and expertise. The didactic model of this workshop is elaborated elsewhere (Fortuin and Bush 2010).

5.4.2 Quasi-experimental design

To answer our research questions, we adapted the EUW. Three workshops (EUW-Brno, EUW-Budapest and EUW-Fosen), offered in the period 6 May – 5 July, 2013 were used in this study. In every workshop three different teachers from various Wageningen University chair groups supervised a different group of thirty students (Table 5.1).

In the original set-up of the course, no specific theory about science–society interactions in interdisciplinary and transdisciplinary research was given. Because theory is one of the elements of our framework a special theory session (2 times 1.5 hour) was developed. This theory training, with lectures and small assignments, introduced students to differences in logic of societal and scientific practices and to the role of values in scientific research. The session also introduced the conceptual model of transdisciplinarity developed by Lang et al. (2012). The session was only offered in the EUW-Budapest and the EUW-Fosen, which were randomly selected. The students in the EUW-Brno worked at that time in subgroups.

Table 5.1 Characteristics of the three workshops (EUWs) involved in the study

	EUW-Brno	**EUW-Budapest**	**EUW-Fosen**
Topic of the consultancy	Developing travel plans to enhance sustainable mobility	Developing travel plans to enhance sustainable mobility	Reinvigoration of the coastal area through aquaculture, recreation & tourism, and wind energy
Commissioner	Nadace Partnerství, an environmental non-governmental organisation	Regional Environmental Center for Central and Eastern Europe	Kysten er klar, an umbrella organisation of several coastal municipalities near Trondheim
Location fieldwork	Brno	Budapest	Coastal area in mid-Norway
Expert analyses executed by students	Policy Stakeholders Mobility Infrastructure Environment & public health	Policy Stakeholders Mobility Infrastructure Environment & public health	Policy & stakeholder Commodity chain Natural resources Social well-being Scenario
Executed in	Five (groups of) companies	Five districts in Budapest	Four municipalities
Participants (30)			
Nationalities	12 Dutch; 6 rest of Europe; 12 rest of the world.	13 Dutch; 4 rest of Europe; 13 rest of the world.	11 Dutch; 8 rest of Europe; 11 rest of the world.
MSc programs	16 Environmental Sciences ; 12 Urban Environmental Management; 1 other	17 Environmental Sciences ; 11 Urban Environmental Management; 1 Aquaculture and Marine management; 1 other	19 Environmental Sciences ; 2 Urban Environmental Management; 8 Aquaculture and Marine management; 1 other
Background supervisors	Environmental technology Environmental systems analysis Methodology & skills	Environmental policy Environmental technology Methodology & skills	Environmental policy Environmental systems analysis Methodology & skills

In all three workshops, teachers stimulated the involvement of all students, facilitated the group dynamics, and watched over the progress through the various phases of the research project. Only in one workshop teachers deliberately scaffolded processes of reflection, in the sense that they actively stimulated students to reflect on norms and values throughout the consultancy research project. This workshop, EUW-Fosen, was randomly selected out of the two workshops with a theory session. In the other workshops, the number of teachers and the total supervision time was the same, but the teachers did not explicitly stimulate reflection.

Before and after the EUW, the participants were asked to fill in a pre-test and post-test questionnaire. At the end of the EUW, all students had to hand in a reflection assignment. Figure 5.2 depicts the research set-up.

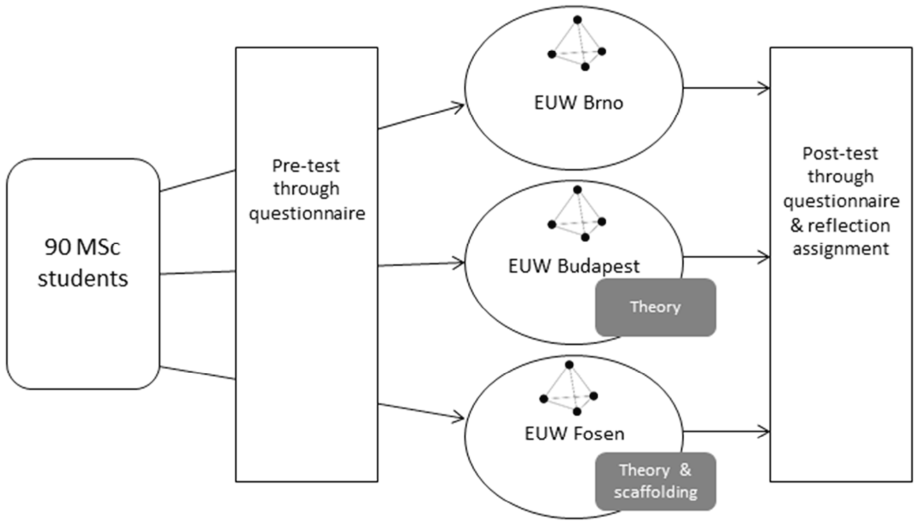

Figure 5.2 Design of the empirical study to test the framework for teaching and learning of reflexive skills

5.4.3 Assessment of inter- and transdisciplinary reflexive skills

As indicated in the introduction, we used both a quantitative approach and a qualitative approach to assess the learning outcomes of the EUW course. The methods of these approaches are described in the next two subsections.

5.4.3.1 Quantitative assessment

Based on the two components of reflexive skills and the underlying theories we deduced learning objectives (see Table 5.2) and a questionnaire. The learning objectives guided the theory preparation for the training session.

The core of the pre- and post-test questionnaire consisted of twenty-five similar statements. All students were asked to indicate on a Likert scale whether they disagreed or agreed with a statement (1-4) or had no opinion. We (the authors of this article) independently assigned a score for reflexivity to every possible answer to a statement. This score ranged from 0-2 (see Table 5.3). Thirteen of the twenty-five questions received similar scores for all possible answers to a statement. Of the statements with different scores, only one differed more than one scale unit for a particular answer. This statement was excluded from the further data analysis. For the other statements, we discussed the differences and then decided on the scores.

Table 5.2 Learning objectives for reflexive skills

Correctly apply the concepts of discipline, value, norm, empirical claim, normative claim, life-world knowledge, interdisciplinarity, transdisciplinarity, transdisciplinary research process.
Explain the difference between societal problem solving and doing scientific research.
Explain the difference between natural and social sciences with regard to their distance to life-world knowledge.
Explain how societal values play a role in scientific research.
Explain potential problems with values in applied scientific research.
Identify disciplinary knowledge aspects in a problem analysis description.
Identify normative aspects in a problem analysis description.
Explain why dealing with values is challenging in transdisciplinary research.
Within an actual project, analyse one’s personal contribution in terms of disciplinary knowledge.
Within an actual project, analyse one’s personal contribution in terms of normative beliefs.
For a given project, indicate how it could be organized in order to improve research outcomes, enhance collective learning, and avoid pitfalls.

Table 5.3 Reflexivity scores attached to the Likert scores for two sample statements of the questionnaire

Statement:	*Disagree 1*	*2*	*3*	*Agree 4*	*No opinion*
In order to improve the sustainability of a city knowledge provided by scientists is more important than knowledge provided by non-academic stakeholders, such as civic associations or environmental non-governmental organisation.	2*)	2	1	0	0
As a scientist I have to be aware of my own opinion and interests, because they might influence my research.	0	0	1	2	0

**) Reflexivity scores can be 0 (low reflexivity), 1 (medium) or 2 (high reflexivity). No opinion was always scored 0.*

In order to check whether the group of statements reliably measured student's reflexivity, we calculated Cronbach's α using SPSS (IBM SPSS version 20). Cronbach's α based on the reflexivity scores for all statements in the pre-test was 0.467. The highest Cronbach's α (0.621) was achieved by removing eight statements. The questionnaire used in our analysis consisted of the remaining seventeen statements (see supplementary material).

We also investigated whether identifying subscales was possible, but found that no reliable subscale could be made, neither for one of the two components of interdisciplinary and transdisciplinary reflexive skills nor for a particular learning objective. Consequently, we only used the overall reflexivity score. We determined the reflexivity score ($RS(S_i)$) of a student (S_i) by calculating the mean of the reflexivity score of this student on the selected seventeen statements (or in case a student skipped one statement, the mean score of remaining statements).

Data were processed in SPSS and significance of differences in RS between pre and post-test was analysed with the Wilcoxon-signed-rank test for non-parametric data (Field 2009, p552-558) because the collected data were ordinal (i.e. students' answers on the Likert scale and attached reflexivity scores) and RS in a group was not normally distributed.

5.4.3.2 Qualitative assessment

Based on their experience in the EUW, students had to write a reflection paper of up to 2000 words which they submitted at the end of the course. The paper was explicitly set up as a reflection assignment to pass the course and was used for our analysis. Students were asked to reflect on using scientific knowledge, working in an interdisciplinary and intercultural group, the process of the research project and the interaction with the commissioner and other stakeholders (the assignment is available as supplementary material). All 90 students handed in a reflection paper.

The reflection papers were analysed in two runs. The first run was meant to determine coding items. Quotes related to the reflexive skills and the learning objectives were identified. These quotes were then grouped into inductively determined coding items. Linking coding items to the specific learning objectives (Table 5.2) proved difficult. The items could, however, well be distinguished into the two categories that correspond with the reflexive skills components: (i) the role of scientific disciplines and non-academic knowledge and (ii) the introduction of norms and values. In the second run, all reflection papers were analysed again using the items determined in the first run. One student [522][1] did not present any information that could be coded and was excluded from the analysis.

5.5 Results

5.5.1 Questionnaire

Table 5.4 shows both the group average (i.e. average $RS(S_i)$ of the students) as well as the range of the reflexivity scores, RS, of all students in each EUW group before and after participating in the EUW. In all three cases, the average RS increased after participating in the EUW. The increase was the smallest in the EUW-Brno and the biggest in the EUW-Fosen. In the EUW-Fosen not only the average, but also the minimum and maximum increased. In the EUW-Fosen, students got both the training and scaffolding.

We found a small but significant increase in reflexivity for the total group of students combined ($T = 857.5$; $p < 0.05$; $z = -2.416$) (see supplementary material). For the EUW-Brno no significant increase in reflexivity ($T = 124.5$; $p > 0.05$, $z = -0.65$) occurred. For the other two EUWs, a medium to large significant increase in reflexivity was observed (for EUW-Budapest $T = 82$; $p < 0.05$; $z = -2.181$ and for EUW-Fosen $T = 81$; $p < 0.05$; $z = -1.974$).

[1] The numbers between square brackets refer to a particular student. Numbers 401-430 are participants of EUW-Brno; 501-530 of EUW-Budapest and 601-630 of EUW-Fosen.

Table 5.4: Group average and range of reflexivity score (RS) in the pre-test and in the post-test

	Pre-test			*Post-test*			*Increase of average RS*
Participated in:	*Average (RSpre)*	*Minimum-Maximum*	*N*	*Average (RSpost)*	*Minimum-Maximum*	*N*	*(RSpost -RSpre)*
EUW-Brno	1.2807	0.82-1.76	26	1.2940	0.76-1.76	29	0.0133
EUW-Budapest	1.2941	0.88-1.88	29	1.3638	0.88-1.88	29	0.0697*
EUW-Fosen	1.2825	0.71-1.63	27	1.4181	0.94-1.82	30	0.1356*
Total	1.2861	0.71-1.88	82	1.3593	0.76-1.88	88	0.0732*

* Significant (Wilcoxon signed rank test, one-tailed, $p < 0.05$)

As the figures show, the highest increase is found for the student group that received both training with theory and scaffolding during the workshop, while no significant change is found for students that received none of the two. Because the workshops not only differed in terms of the quasi-experimental design, but also in several other ways (different student groups, different consultancy aims, different locations), it cannot be excluded that these findings were caused by other factors than the learning and teaching elements. Even when individual differences between students were accounted for in pre-post-test design, and training elements were randomly assigned to the three groups, the results of the quasi-experiment have less evidential value than a fully randomized experiment. Still, the results clearly support the idea that mere involvement and interaction in research that invites for reflexive practice is not sufficient for students to significantly improve their reflexive skills. They also indicate that theory training can be an influential element of an adequate teaching and learning framework, and that scaffolding, too, can have a positive impact.

5.5.2 Reflection assignments

Before describing the findings concerning the role of various sorts of knowledge (5.5.2.2) and the introduction of norms, values and interests (5.5.2.3), we first present some general findings that are not specifically linked to one of the two components of reflexive skills.

5.5.2.1 Salient characteristics of the student reflections

A striking, though not unsurprising, characteristic of almost all reflection papers was that they were strongly coloured by personal experiences that sprung from situational workshop characteristics. What students, for example, mentioned as the most important contribution of their consultancy project differed. Seventeen students from the EUW-Brno reported that they presented a new perspective to their commissioner. They discovered that a fundamental obstacle to promoting sustainable mobility in Brno was a lack of communication and collaboration between stakeholders and the lack of an organisation that wanted to initiate or lead the mobility plan's development. In the EUW-Budapest, sixteen students reported that they provided the commissioner with a comprehensive overview of the existing state of infrastructure and mobility in Budapest. In the EUW-Fosen, nineteen students reported that they provided their commissioner with a variety of valuable and original recommendations to reinvigorate the area.

Another salient finding was that nearly all (i.e. 23; 28; 29)[2] students in all three workshops realized that throughout the research process choices needed to be made that influenced the direction of the research. They observed that these choices were not only influenced by personal preferences and expertise, but also by the communication and interaction among the participants and the group dynamics. They were aware that all these choices ultimately influenced the research outcomes and the recommendations as is illustrated by the following quote:

> Strong personalities had fewer difficulties to push their ideas whereas others did not dare to participate, regardless of the quality of their ideas. For instance, from the five different analyses, I felt the policy analysis dominated at the end of the workshop [617].

5.5.2.2 The role of scientific disciplines and non-academic knowledge in the EUW project

Tables 5.5 shows items related to the role of scientific disciplines and non-academic knowledge in the EUW project (c.f. first component reflexive skill) frequently mentioned by students in their reflection papers as well as how frequent they were addressed in the three EUWs.

Most students (17; 18; 22) mentioned that a broad interdisciplinary approach was needed to address the issue they were confronted with. They considered both scientific knowledge from various disciplines and local knowledge crucial to address the issue. Many students (6; 11; 12) valued the importance of scientific knowledge. Some (4; 2; 9) reported that they used scientific knowledge in particular in the beginning of the project when it helped them to frame the issue and to formulate research questions. They used scientific methods to collect

[2] The figures between brackets refer to the amount of students who mentioned this in their reflection paper in the order: Brno, Budapest, Fosen.

and analyse data, but the time constraints later in the project limited using scientific literature.

Table 5.5 Items related to the role of academic and non-academic knowledge and their frequencies in students' reflection papers in the three EUW-projects

Students report:	**Brno (%)**	**Budapest (%)**	**Fosen (%)**
that scientific knowledge from various disciplines as well as local knowledge is needed to address the issue.	57	60	73
that knowledge held by stakeholders is needed to address the issue**.**	27	57	50
that it is necessary to experience the local situation.	20	37	23
that the use of scientific knowledge and methods is important to address the issue.	20	37	40
that the diversity of the group (interdisciplinary and intercultural) makes it possible to have a broad perspective which enriches the outcome.	53	80	83
that they have been struggling with the integration of divers knowledge, data, methods, or theories.	33	30	53
that they have *not* been struggling with the integration of divers knowledge, data, methods or theories.	10	10	10
that they like the interdisciplinary approach because it confronts them with new perspectives and enables them to learn from others.	30	33	47
nothing relevant on academic and non-academic knowledge	10	10	3

Many students (8; 17; 15) valued the knowledge held by stakeholders. They appreciated local stakeholders' opinion and realized that they could only acquire this knowledge by talking to them. Some students (6; 11; 7) also mentioned that they needed to be in the area to better experience the local situation, to fully understand the issue and to be able to formulate relevant recommendations. Solutions that seemed all right in theory turned out to be difficult to implement. Few students (1; 0; 2) reported that they were struggling with the reliability of stakeholder knowledge, as is illustrated by the following quotes:

> In the interviews, they [*i.e. local stakeholders*] were giving us more of their personal opinions rather than an expert analysis and I was wondering how to make a scientific report out it [404].
>
> In literature I found a lot of information about the environmental impacts of aquaculture. However, once we were in the field, the people we interviewed told us that the impacts were

> very small. But how reliable is a single person, who is a representative of a very large company? [...]. A research institute might be more reliable than a commercial company, if we are talking about environmental impacts [625].

Most students (16; 24; 25) appreciated the interdisciplinary approach and the diversity of the whole group, because it enabled them to use a broad perspective. This enriched the outcome of the project. Many (10; 9; 16) also reported that they had been struggling with the integration of data from different types of knowledge or disciplines. A minority (3; 3; 3) recounted that they did not experience any cross-disciplinary problems because they were all studying similar topics in Wageningen or because they did not have to integrate theories from various disciplines.

Many students (9; 10; 14) appreciated the interdisciplinary approach that confronted them with new points of view and enabled them to learn from others. In particular natural science students (4; 1; 3) learned to appreciate the value of social science and mentioned that they gained a better understanding of social science and thus the studied issue. An environmental engineer wrote:

> I discovered that I like to focus on social science. [...] Social science is crucial to complete the gap of natural science studies which often miss to fulfil the society's needs [629].

A minority (0; 3; 0) reported that they welcomed the interdisciplinary approach because they could focus on their own expertise while the broader perspective was still safeguarded.

5.5.2.3 The introduction of norms, values and interests in the EUW project

Table 5.6 shows items related to the introduction of norms, values and interests in the EUW project (c.f. second component reflexive skill) frequently addressed by students in their reflection papers as well as how frequent they were addressed in the three EUWs.

Table 5.6 Items related to the introduction of norms, values and interests and their frequencies in students' reflection papers in the three EUW projects.

Students report:	Brno (%)	Budapest (%)	Fosen (%)
that values and interests are introduced in the problem framing phase (ToR).	23	37	47
that the project is influenced by the values or interests of the commissioner.	50	37	23
about values in data collection. They mention that the people they interview have various interests, and that values might influence the interpretation of the observation scheme.	10	23	37
that in the data analysis choices need to be made that influence the outcome of the study.	13	7	27
that a field of science might influence normative choices in a research.	17	27	57
that cultural background might influence normative choices in a research.	30	37	27
that the formulation of recommendations was influenced by norms, values, or interests.	47	53	60
their own values and normative choices.	13	30	23
nothing relevant on the introduction of norms and values	17	17	3

Most (25, 25, 29) students reported on the introduction of values in the consultancy project in their reflection papers. Fifteen students in the EUW-Brno recounted about the influence of the commissioner, Nadace Partnerství (NP), an environmental non-governmental organisation with a clear vision on sustainable mobility. These students reported that the commissioner's values influenced the problem framing and data collection but in particular, the formulation of the recommendations. Fifteen Budapest and only eleven Fosen students mentioned the influence of the commissioner. The influence of commissioner in Budapest, the Regional Environmental Center for Central and Eastern Europe (REC), appeared to be less prominent partly because the topic was less relevant for REC and REC was not responsible for Budapest's mobility strategy. REC could only try to put sustainable mobility on the municipality's agenda. The Fosen commissioner, Kysten er klar, did not promote any particular opinion or interest, instead the commissioner indicated to be interested in recommendations based on a broad multidisciplinary perspective and an 'outsiders' view'. Although the Budapest and Fosen commissioners were less outspoken than the commissioner of the Brno-group, many students from these two workshops still realised that values were introduced by the Terms of Reference (ToR) (Budapest: 11; Fosen: 14).

Compared to the Brno-students, the Budapest and Fosen students became more aware of their *own* values and interests (see Table 5.6). They also more perceptively, i.e. with more precision and detail, articulated this in their reflection papers. The students realized that they themselves influenced the research and mention that these values influenced all stages of the research project, the problem framing, the methodology, the data collection and the formulation of the recommendations.

Only five Brno students mention that their environmental background influenced the project, compared to eight Budapest students and seventeen Fosen students. In the latter workshop not only environmental students participated but also a rather big group of students in aquaculture and marine management (for group composition see Table 5.1). It seems that differences in disciplinary norms and values become more prominent when the differences between the scientific fields are apparent. The following quote illustrates how a student was triggered by this:

> I noticed that most Aquaculture and marine management students were absolutely convinced of the beauty and potential of aquaculture. Aquaculture is the future and environmental impacts hardly exist according to them, which is not strange when taking their background into account [613].

Nine students in the EUW-Brno mentioned that their experience in the Netherlands and their Dutch perspective influenced their research. To illustrate this, they all refer to the emphasis on cycling in their research. Eleven students in the EUW-Budapest report on the influence of their cultural background. These reflections were related to both the problem perception and the formulation of recommendations:

> For some students, the mobility in Budapest was good and they did not perceive a big problem related to the infrastructure and mobility. For others it was different. I believe that this was influenced by our cultural background [....]. If I compare the mobility in Budapest with the mobility of Bogotá, the capital of Colombia, where I am from, I think that Budapest does not have any problem, but students from the Netherlands, where the different modes of transport are very well organized, perceived problems that for me would not be relevant [504].

> We perhaps unconsciously compared and judged mobility management in Budapest to our notion of ‘good (mobility) governance’. We assumed that decision-making should be very participatory and balance all interests. This is reflected in our recommendation ...[...]. Perhaps we could have reflected more on what kind of ‘governance-style’ fits Budapest best [523].

Only eight Fosen students reported on cultural norms and values. These students more than the other two EUW groups reported on various stakeholder interests:

> People [*we interviewed*] ... saw our research as an opportunity to serve their interests in a way. I believe that we were aware of those various interests affecting the data collected and tried to keep the interpretation value-independent as much as possible [629].

Some students (1; 2; 4) considered that the multidisciplinary and multicultural composition of the group safeguarded a good outcome because different perspectives were counterbalanced:

> I am convinced that we respected a well-balanced outcome as a compromise between different values developed through our different educations. ...[...]. Values were involved in the whole process, in every phase, but we kept aware of that because we discussed our different values. This is also why a mixed group is good if we want to be as objective as possible [616].

5.5.2.4 Reflection papers, in sum

Overall, almost all students in the three EUWs appreciated the transdisciplinary approach and the diversity of the students involved in the project. The students in the EUW-Budapest and Fosen reported more explicitly about the difference between academic and non-academic knowledge and they were also more sensitive to the norms, values and interests in their project than the students from the EUW-Brno. Almost all students realized that throughout the research process choices needed to be made that influenced the direction of the research. A substantial part of them observed in their papers that these choices were influenced by preferences of students and other stakeholders (including norms and values), by the students' expertise (from more or less diverging disciplinary backgrounds) and by the interaction among the students or the group dynamics. Most of them appear to be aware that all these choices ultimately influenced the research outcomes and the recommendations. Hardly any (0; 0; 2) of the remarks relevant to reflexive skills, however, did explicitly refer to theory presented in the training, and the remarks did not specifically refer to the learning objectives as we formulated them in preparing this theory training; they were written on a more applied and personally coloured note.

5.6 Discussion

The aim of this paper is to present and evaluate a framework for teaching and learning of reflexive skills. In order to assess students' reflexive skills, we needed to operationalize these skills. Clearly, operationalizing and assessing reflexive skills and developing a teaching and learning strategy are closely intertwined. While the need for reflexivity is frequently observed in literature on higher education, the development of mechanisms to monitor and assess reflexive skills has not been a priority, among others because different views on reflexivity's scope exist (Smith 2011). An instrument for assessing reflexive skills is, however, needed to evaluate the output of educating researchers with reflexive skills. Moreover, the development of such an instrument provides the opportunity to more tightly define what is meant by reflexive skills. Combining operationalization and assessment with design of strategies proved a very useful way of articulating key aspects of reflexivity, identifying knowledge gaps, and moving forward in educational practice.

Using an authentic educational setting to evaluate the framework for reflexive skills has drawbacks. There were many practical differences between the three workshops, used in this study springing from the specific consultancy assignment, the location in which the research took place, the involvement and responsibilities of the commissioner, the group composition and dynamics, and the different teachers supporting the groups. These differences obviously influenced the results. We combined a quantitative testing approach with a more qualitative analysis of the reflection papers to cross-check the findings and so to arrive at more robust outcomes.

Obviously, quantitative assessment of reflexive skills is very complicated. We formulated learning objectives for reflexive skills, developed statements, and assessed students based on reflexivity scores attached to answers on a Likert scale. While this procedure served its purpose of comparing the learning outcomes in the experiment, it also made clear that it is very difficult to operationalize reflexive skills through a series of closed statements. As mentioned before, we removed eight of the original twenty five statements from the questionnaire, one because the scoring for reflexivity differed too much between the authors, the other seven in order to improve Cronbach's α. We suspect that these removed statements were too complex or included specific terms that students did not sufficiently master. A lesson learned is that to measure reflexivity, the statements should not be too obvious but also not too ambiguous; a balance between the two needs to be found.

It would be of great help to have more robust guidelines for constructing questionnaire instruments to assess reflexivity. One way of moving forward could be to further develop theory on reflexivity in transdisciplinary research and use this as basis for better guidelines. Another way of moving forward could be to make comparisons with assessment methods in other complex domains, such as medical education, or the development of intercultural competence. An interesting example, in this respect, is the Intercultural Development Inventory, a questionnaire to measure intercultural competence or intercultural sensitivity of persons (Hammer et al. 2003; Hammer 2011). Formulating good statements for the questionnaire also requires more insight in students' reasoning on different aspects of reflexivity. The analysis of the reflection papers in this research provided some of these insights.

Clearly, what students wrote in their reflection papers was influenced by the formulation and requirements of the reflection assignment, by a student's interpretation of this assignment, and by his/her writing abilities. Hence, what students reported is not the same as what they learned. Still, analysing the reflection papers provided us with a more in-depth understanding of students' experiences and their perspectives on the teaching and learning framework. Moreover, such a reflection assignment can also serve as an element of the teaching and learning strategy.

In this paper, we presented four key elements for teaching and learning of reflexive skills. We will discuss each of these elements in the order: experience, others, theory, and reflection.

The analysis of the reflection papers clearly showed that the students' learning was very much determined by their personal *experiences*. The experience in every EUW was different because, for instance, the consultancy assignment, the involvement and responsibilities of the commissioner and the group dynamics differed. This influenced what students reported. We also found that what students reported in their reflections, was very much triggered by the commissioner or outspoken stakeholders they met or by the other students. Differences in disciplinary norms and values became more prominent when the differences between the available scientific fields were sufficiently large and when the group of students was diverse enough. In other words, students' learning was strongly influenced by the interaction with *others*.

Although very few students explicitly referred in their reflection papers to the *theory* that was provided, there are indications that the theory training positively influenced their reflection. In the reflection papers, students who received the training more often and more perceptively reported on the influence of values and interest in their research than students who did not receive this training. The quantitative assessment of reflexivity improvement supports this finding. Together, our results suggest that the theory sessions provided students with a better frame of reference for developing their reflexive skills, even when a more explicit embedding of this theory in their way of reasoning was not much observed.

Explicit moments of *reflection* were incorporated in the form of a reflection assignment and scaffolding. Our statistical results suggest that in addition to theory, scaffolding augmented the learning of reflexive skills. Because the reflection paper was made by all experimental groups, we cannot make supported claims on the impact of this assignment. Nonetheless, it is likely that the paper writing will have stimulated students to reflect (Aronson 2010).

These findings on the roles of theory and scaffolding are in line with several other studies stating that students need support to reflect and that without a theoretical base students' reflection can remain superficial (Van der Lecq et al. 2006; Feng 2011; Smith 2011; Thompson and Pascal 2012; Wagner et al. 2013).

5.7 Conclusions

Our study shows that training students' interdisciplinary and transdisciplinary reflexive skills is possible in environmental science education, but it requires a well-designed learning setting. Combining theory on reflexivity-relevant concepts, experience of concrete transdisciplinary projects, close interaction and debate with persons with other scientific background and interests, and explicit moments of reflection contribute to learning reflexive skills. Submerging students in a situation where they must integrate theory and practice, and where they are confronted with divergent values and interests, is a good starting point to train reflexive skills. Our findings show that actual research experiences and interaction with others largely shape students' perception of the contribution of disciplines, of science-society interactions, and of the embedding of norms and values in a transdisciplinary environmental research project. However, experience and interaction with others seem not sufficient. Our study points out that it is valuable to provide theoretical training, and to stimulate explicit moments of reflection, for example, by scaffolding. Our study also pioneered the operationalization and assessment of reflexive skills. It shows that it is possible to quantitatively measure changes in reflexive skills, but also lays out some of the difficulties in categorizing these skills and constructing robust questionnaire instruments.

These conclusions clearly invite for further research. With regard to the teaching and learning framework, we need deeper insight in which theoretical concepts are most relevant to reflexive skills in interdisciplinary and transdisciplinary research and how to teach them. In the research for this article, we made some steps in this respect – it is beyond our scope to elaborate them here – but much more is needed.

6 Synthesis

6.1 Introduction

The complexity of environmental problems has undeniably increased during the last decades. Current complex environmental problems span broad spatial, temporal and organisational scales, are multi-dimensional and involve political controversies. Complex environmental problems are further characterized by many uncertainties, conflicting views on the nature of the problem and the best way to solve them (Giller et al. 2008; Kueffer et al. 2012).

Addressing the current environmental challenges requires new ways of collaboration between academic and non-academic stakeholders. Not only multidisciplinary and interdisciplinary approaches (in particular involving or integrating natural science, social science and humanities), but also transdisciplinary approaches (i.e. involving non-academic stakeholders) are needed to effectively respond to the current challenges and to develop sustainable solutions for complex environmental problems (Lang et al. 2012; Rice 2013; Mauser et al. 2013; Kerkhoff 2014). Leading or executing interdisciplinary and transdisciplinary projects requires specific competencies of the environmental scientists involved. Environmental science course and curriculum developers are confronted with the challenge to educate these scientists.

All over the world, efforts exist to timely adjust curricula to meet current environmental and sustainability challenges (e.g., Vincent and Focht 2011; Clark et al. 2011a; Barth and Michelsen 2013), but generally accepted frameworks to educate environmental science graduates with the necessary competencies to address complex environmental problems are scarce (Camill and Phillips 2011; Proctor et al. 2013). Building on the experiences at Wageningen University and elsewhere, I explored and developed principles and heuristics (i.e. 'rules of thumb') for teaching and learning activities that enable environmental science students to acquire boundary crossing skills. These skills are needed to develop sustainable solutions for complex environmental problems. I focussed on interdisciplinary and transdisciplinary cognitive skills as a sub-set of boundary crossing skills, and on the potential contribution of conceptual models and environmental systems analysis in teaching and learning these skills. The aim to develop heuristic principles to teach and learn boundary crossing skills in environmental science education, resulted in the following questions that guided my research:

Q1. What are boundary crossing skills that enhance students' ability to understand complex environmental problems and develop sustainable solutions?
Q2. What can conceptual models contribute to develop these skills?
Q3. What can education in environmental systems analysis contribute to develop these skills?
Q4. What are heuristic principles for teaching and learning activities to develop these skills?

In order to answer these research questions, I did four studies, elaborated in Chapters 2-5. These studies were based on an extensive literature review, analysis of existing courses and course material, personal experience and analysis of reflection papers written by students in authentic learning settings. The last study (Chapter 5) was an empirical statistical study. I developed a strategy for teaching and learning reflexive skills, a subcomponent of boundary crossing skills, and evaluated this strategy in a quasi-experimental setting.

As the former chapters describing these studies have shown, operationalizing skills and developing teaching and learning activities are closely intertwined. In presenting the conclusions of this thesis, however, I discuss the skills and the teaching and learning activities successively. I start in Section 6.2, with a map of boundary crossing skills (i.e. Q1). Next, the contributions of conceptual models (Section 6.3; Q2) and environmental systems analysis (Section 6.4; Q3) to environmental curricula and courses are explicated. Finally, the findings of all studies are combined into heuristics principles for teaching and learning boundary crossing skills in environmental science education (Section 6.5; Q4).

6.2 Boundary crossing skills operationalized

In the context of environmental science and education for sustainability, competencies are a much-discussed topic (e.g., Martens 2006; De Kraker et al. 2007; Vincent and Focht 2011; Rieckmann 2012; QAA 2014). In these discussions, the need to specify core competencies to successfully contribute to environmental problem solving and sustainable development, and to address these explicitly in the educational curriculum is widely acknowledged. Specified core competencies help clarifying learning outcomes (i.e. the product or outcome of the teaching and learning system). Clear learning outcomes are required to design effective learning activities and to structure the learning experience (Biggs 1999). Moreover, clear learning outcomes are needed to satisfactorily assess students' achievements and the overall effectiveness of courses and curricula (Biggs 1996; Boix Mansilla et al. 2009).

Vincent and Focht (2011) made a useful step towards specifying core competencies for interdisciplinary environmental degree programs. They distinguished three interdisciplinary knowledge areas: (i) natural sciences; (ii) coupled human-nature systems; and (iii) economic development. They also identified two integrated skills areas: (i) problem analysis skills and (ii) problem solutions and management skills. Cognitive skills were highlighted as a key element for both the analysis of environmental problems and the formulation of solutions. Vincent and Focht (2011) also stressed the importance of further exploring and specifying these knowledge and skills areas. Taking up their challenge, I operationalized cognitive skills for interdisciplinary environmental science education. I distinguished boundary crossing skills, interdisciplinary and transdisciplinary cognitive skills, and reflexive skills (Figure 6.1).

I explained that addressing complex environmental problems requires crossing boundaries between disciplines, between cultures and between theoretical knowledge and practice (Chapter 2). Within boundary crossing skills, I made a distinction between knowledge, attitudes and skills referring to the extent to which students (i) *are aware* of different disciplinary, cultural, theoretical or practical perspectives, (ii) *acknowledge the value* of using these perspectives in addressing complex environmental problems, and (iii) *are able to* use various disciplinary perspectives and connect them; and *are able to* collaborate, negotiate and make decisions in intercultural settings, and to deal with complexity and uncertainty.

Interdisciplinary and transdisciplinary cognitive skills are a sub-set of boundary crossing skills. They enable a person to integrate knowledge and modes of thinking in two or more disciplines to produce a cognitive advancement (e.g., solving a problem) (Boix Mansilla and Duraising 2007). These cognitive skills are crucial for both appropriately analysing a societal issue (i.e. an environmental problem) and for using and integrating knowledge to create sustainable solutions. As such, they enable a student (or expert) to cross boundaries between societal practice and theoretical knowledge, and between disciplines. Interdisciplinary and transdisciplinary cognitive skills are complex skills comprising several components (van Merriënboer 1997). I distinguished three component skills (Chapters 3 and 4; Figure 6.1).

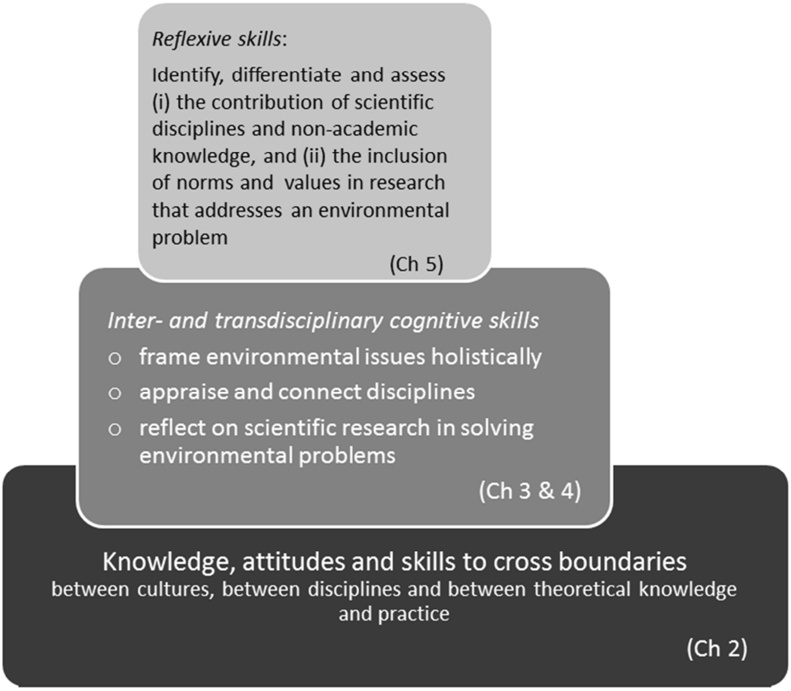

Figure 6.1: The components of boundary crossing skills distinguished in this thesis

The first component skill is the ability to understand environmental issues in a holistic way (i.e. considering different perspectives, systemic social and biophysical elements and their dynamics and interactions). The ability to frame environmental problems holistically allows a comprehensive insight into all relevant aspects to possibly solve the studied problem. This ability implies that students are able to frame an environmental problem not only as a pollution problem, but also as a policy problem or as a problem embedded in a specific cultural context. Consequently, proposed solutions cover technological, but also financial, social, behavioural or legislative issues, and they might involve local, national and maybe even international stakeholders. This first component skill helps students to recognize the relevance of using different disciplinary perspectives in addressing an environmental issue.

The second component skill is the ability to identify, understand, critically appraise and connect disciplinary theories, methodologies, examples and findings into the integrative frameworks required to analyze environmental problems and to devise possible solutions. This ability is related to 'disciplinary grounding' and 'integration'. Disciplinary knowledge in environmental science is used as a means to a purpose. It is used to analyze an environmental problem and develop solutions. A student needs to have enough understanding of major relevant disciplines to be able to select and connect (or integrate) disciplinary knowledge and methods accurately and effectively and to appraise their contribution to a problem. The environmental problem at hand determines which disciplinary knowledge is needed and how this is to be integrated with other knowledge (Chapter 4).

The third component skill is the ability to reflect on the role of disciplinary, interdisciplinary and transdisciplinary research in solving societal problems. While the second component skill is about understanding, using and connecting major disciplines, the third component skill is about critically assessing the role of science in society. It encompasses reflecting on the processes of knowledge production and application. I introduced the term 'reflexive skills' for this third component. Reflexive skills refer to the ability to question the different sorts of knowledge used, to recognize the epistemological and normative aspects involved, and to reflect on one's own and others' roles in these knowledge processes. This reflection is crucial when cooperating in interdisciplinary projects, but especially in transdisciplinary projects in which non-scientific stakeholders from local communities or governments are involved as well. Environmental students and scientists need to be able to reflect on the value of what they know, how they obtained such knowledge and the inherent uncertainties and other limitations of this knowledge. Mastering this third component skill helps them to adequately deal with the normative choices, opportunities, compromises, stakes and limitations that are part and parcel of practice-oriented interdisciplinary and transdisciplinary research (Chapter 4).

I operationalized reflexive skills and distinguished two sub-components on three skill levels (Chapter 5; Figure 6.1). These subcomponents are (i) the ability to identify, differentiate and assess both the contributions of relevant scientific disciplines and non-academic knowledge to address an environmental problem, and (ii) the ability to identify, differentiate and assess the inclusion of norms, values and interests into a research process that addresses an environmental problem, and thus into the design of strategies, technologies or scenarios that address this problem. These skills can be assessed on three levels: (a) a general level (i.e. science in general or an environmental problem in general); (b) the level of a specific project; and (c) the individual's level (i.e. one's own position and contribution in terms of scientific and other knowledge, and interests, norms, and values in addressing a problem). All three levels are relevant for interdisciplinary and transdisciplinary research.

Clearly, in order to assess students' achievements and the effectiveness of courses and curricula, all these skills need to be further operationalized. Based on the two subcomponents of reflexive skills specifically and the underlying theories, I deduced learning objectives and developed a set of statements. I used these statements in a student questionnaire to quantitatively assess their reflexive skills. I showed that it is possible to measure changes in reflexive skills. I could, however, not assess the specific learning objectives nor distinguish the three levels via the set of statements. Obviously, to operationalize and assess reflexive skills through a series of closed statements is very difficult. Formulating good statements requires insight in students' reasoning on different aspects of reflexivity. The analysis of students' reflection papers provided some of these insights. These papers showed that the two components of reflexive skills (i.e. the role of academic and non-academic knowledge, and the introduction of norms, values, and interests) could well be distinguished (Chapter 5).

6.3 The contribution of conceptual models to environmental science education

The interdisciplinary or transdisciplinary and problem-oriented character of environmental science curricula challenges curriculum and course developers in two interrelated ways. The first challenge concerns the structure of a curriculum: How does one design a coherent curriculum, while including various disciplines? Environmental science curricula often encompass courses or course tracks from particular disciplinary angles together with integrating courses, seminars and work groups (Maniates and Whissel 2000; Clark et al. 2011b; Wei et al. 2015). But which disciplines should be central in this curriculum and how detailed should students be educated within each of them? What is the proper place for integrating elements and how can these elements be organized? And, last but not least, how can students gain an overview of the curriculum's structure, so that they can understand how specific course contents fit within the bigger picture? This challenge of program structuring has been reported in many studies (e.g., Soulé and Press 1998; De Groot and De Wit 1999; Maniates and Whissel 2000; Chapman 2007; Vincent and Focht 2009; Proctor et al. 2013).

The second challenge is teaching integrated problem-solving. How can students be stimulated to develop the ability to analyse and solve complex problems? This second challenge follows from the previous one. It is insufficient that students acquire relevant combinations of disciplinary knowledge and skills, and participate in integrating courses or workshops. In doing so, they also need to learn how to integrate knowledge and skills in dealing with complex environmental problems (see e.g., Scholz and Tietje 2002; Vedeld and Krogh 2005; Fortuin and Bush 2010; Clark et al. 2011b).

Based on literature research, analyses of courses and course material, and personal experience and communication, I showed that conceptual are valuable for meeting these characteristic challenges for environmental science education (Chapter 3). Conceptual models are abstract representations of reality. These models are usually depicted as two-dimensional diagrams consisting of circles or boxes showing the main elements, processes or variables of a system and lines or arrows explaining the relationships among them.

I introduced two types of conceptual models: domain models and process models. Domain models describe components and processes involved in environmental problems. They indicate the subject area of environmental science. Typical examples of this type of models are the DPSIR (**D**riving forces – **P**ressure – **S**tate – **I**mpact – **R**esponse) model (Smeets and Weterings 1999; Bell 2012) and the Millennium Assessment Framework (Millennium Ecosystem Assessment 2003). Process models depict the different steps in an environmental research process and clarify how these steps are related to the societal processes important to the research (i.e. how they are related to environmental problem-solving). Examples of process models are the 'van Koppen and Blom (1986)' model for problem-oriented research and the 'Jahn (2008)' model for transdisciplinary research. Both domain and process models are meaningful for environmental science education but they have different strengths and applicability (Chapter 3).

Domain models, in particular the DPSIR model, can be used to improve the coherence and focus of an environmental science curriculum, in particular a curriculum with an *environmental problem solver* perspective. Disciplinary scientific knowledge can be easily located within the DPSIR model. Practitioners of the natural sciences (e.g., biology, hydrology, physics and chemistry) study the environmental pressures, states and impacts through the investigation of, for instance, the emission of pollutants and their effects on organisms and ecosystems. Practitioners of social-science disciplines (e.g., sociology and economics) investigate drivers, the societal causes of environmental problems, and pressures. Those in environmental technology and environmental policy and management investigate responses in order to mitigate or solve the problem. DPSIR's 'discipline-oriented' character makes it a suitable framework to connect various disciplinary elements within an environmental science curriculum. Its 'problem-oriented' character helps to focus and to select among the abundance of disciplinary knowledge. The model helps determine which disciplinary knowledge is relevant enough to be taken into account; namely the knowledge that is useful for understanding why there is, for instance, a pollution problem, what the characteristics are of this pollution problem, and how it can be mitigated. The DPSIR model can thus be used as a framework to assist students in seeing connections between different elements of a curriculum or course, and as a conceptual tool that assist those students in analysing an environmental problem and identifying ways to mitigate it.

Both the DPSIR model and the MA framework can be used in an individual course as an explanatory illustrative framework to analyse the interactions in human-environment systems and to integrate knowledge from various disciplines. They are, however, not meant to provide an overall theory. Instead, they can be used as a broad, flexible framework to environmental problems and their solutions, and to integrate divergent knowledge (Chapter 3).

Process models can be introduced to students along with a research project on a realistic environmental problem. They can help students in reflecting on both the societal and ethical implications of that research, and their role as scientists in solving a societal problem.

The model for problem oriented research developed by van Koppen and Blom (1986), for instance, is a combination of a model describing the different steps in solving a problem and in doing research (i.e. the empirical circle). This model highlights that in problem-oriented research, science becomes involved in a societal process of problem solving. The van Koppen and Blom (1986) model helps students to understand the differences between problem solving as a societal process and scientific research, and to distinguish different steps that are relevant to problem-oriented research. For instance, it helps them to see that defining a problem is a normative process determined by stakeholders, that their scientific models provide only a partial view on the problem domain, and that a good scientific outcome as such does not solve the societal problem (Chapter 3).

The Jahn (2008) model provides a characteristic and clear representation of transdisciplinary approaches. This model highlights the complexity and different perceptions of the problem and the research process. Several research questions, which will require their own scientific methodologies, need to be formulated to tackle the full complexity of the problem. At some point, the diverse perspectives in the Jahn (2008) model have to come together. The integration of divergent concepts, scientific knowledge, and practical knowledge and needs, is explicitly addressed in this model (Godemann 2008). Moreover, the Jahn (2008) model illustrates a continuous dialogue and interaction between the scientific world and society (Chapter 3).

Process models provide teachers and students with a tool (i) to explain the difference between societal problem solving and doing scientific research; (ii) to explain and analyse characteristic stages of transdisciplinary research processes and to discuss basic methodological implications (e.g., problem framing, producing knowledge and integrating and applying knowledge); and (iii) to identify and explain normative aspects in the transdisciplinary research process (Chapters 3 and 5).

Although these two model types are valuable for structuring environmental science education, none of them is sufficient to become the only unifying framework. Rather, specific models should be used at specific moments with the more complex models (e.g., the Jahn (2008) model) situated at later stages in a curriculum. In the beginning of a study program (e.g., Bachelor of Science level), the older, more linear models (e.g., the DPSIR model and the van Koppen and Blom (1986) model) can guide students in their first stages of mastering environmental science. These simple models are still adequate for many environmental issues. Later, in the master and PhD phases, more-encompassing and complex integrative conceptual models that include feedback systems and interactions between phenomena on different temporal, geographical, and organizational scales, should be used. Models in which the full complexity of human-environment systems is addressed and in which the need of integrating divergent perspectives to fully comprehend this interaction is indicated ought to be part of graduate and postgraduate environmental science education (Chapter 3).

To expose students to a range of conceptual models during their education is essential, because such a variety is instrumental in enhancing the students' awareness of the various approaches to frame environmental issues and to illustrate and explain how this framing has changed over time or what its consequences are. By applying and reflecting on these conceptual models, students likely acknowledge the complexity of human-environment systems and science's role in dealing with complex environmental problems (Chapter 3).

6.4 The contribution of systems analysis to environmental science education

Environmental systems analysis (ESA), which is an integrative discipline within the environmental sciences, aims at improving decision making by providing relevant and structured knowledge on the environmental problem itself, the range of potential responses to the problem and the consequences of these responses (Quade and Miser 1997; Olsson and Sjöstedt 2004). As a scientific field ESA aims to develop and apply integrative tools, techniques and methodologies to better understand environmental problems from different perspectives, including natural and social sciences, society, economy and technology and to develop sustainable solutions for these problems (Björklund 2005; Ahlroth et al. 2011). Typical ESA tools are life cycle assessment, environmental impact assessment and scenario analysis (Finnveden and Moberg 2005; Höjer et al. 2008). ESA education likely improves students' boundary crossing skills.

Based on a case study in a BSc ESA-course at Wageningen University and literature research, I showed that education in environmental systems analysis improves students' knowledge about integrative tools, techniques and methodologies, and their application, but also – to a certain extent – their interdisciplinary and transdisciplinary cognitive skills (Chapter 4).

For the first component skill – the ability to understand (environmental) issues in a holistic way, whilst considering the interplay of social and biophysical dynamics – ESA has much to offer. The ESA's tools, methods and models help to conceptualize and frame an environmental issue holistically and to connect and integrate disciplinary knowledge and methods. By applying these tools, methods and models to environmental problems, students become aware of the broader context of an environmental problem, its direct and indirect causes, and its direct and indirect effects, the probable connections between local and global issues and the interaction with various societal actors and stakeholders (Chapter 4).

For the second component skill, ESA education likely enhances students' ability to identify and connect disciplinary approaches in integrative frameworks, but only enhances the students' ability to critically appraise disciplinary approaches in integrative frameworks to some extent. Education about systems theory provides students with insight in the nature of (sub)systems (e.g., technical, biophysical or social systems). Education about ESA's tools and methods assists students to structure environmental issues and helps to integrate disciplinary knowledge. Applying ESA's tools and methods helps students to realize that there are various disciplinary approaches, each with their own disciplinary perspective, that are relevant to study an environmental issue. In order to be able to appraise the contribution of such a disciplinary approach to a specific environmental problem, students need to have sufficient disciplinary knowledge and disciplinary education (i.e. education on disciplinary theories, concepts and methodologies) is needed (Chapter 4).

ESA supports the training of the third component, the ability to critically reflect on the role of disciplinary and interdisciplinary research in solving societal problems, but more is needed. Students experience difficulties with reflecting on the role of science in solving complex societal problems. Systems analysis can support reflection by making students aware that a system always represents a simplified model and a particular perspective of reality, but training students to be reflexive is complicated. Systems analysis and conceptual models can only be supportive to a certain extent (Chapter 4). In order to train students in reflexive skills specific teaching and learning activities are needed. These are addressed in Section 6.5.

6.5 Heuristic principles for teaching and learning boundary crossing skills

This last section combines the findings in the previous chapters in order to provide heuristic principles for teaching and learning boundary crossing skills in environmental science education. To get an understanding of the teaching and learning system, I introduced the 3P-model of Biggs (1999) (Chapter 1). Biggs' (1999) 3P-model of teaching and learning distinguishes the **P**resage, the **P**rocess and the **P**roduct stages to describe the interaction between the student, the teacher, the teaching context, the learning activities and the learning outcomes. Presage involves the student and the teaching context that both foreshadow the educative process. The teaching context not only encompasses the content to be taught, how this will be taught, the expertise of the teacher, the teaching and assessment methods used, but also the curriculum or the institutional characteristics in which a curriculum or course is embedded. Students' factors together with the teaching context (from the Presage stage) determine the activities that a student undertakes in the Process stage. These 'learning activities' (i.e. what a student does) in turn lead to learning outcomes in the Product stage.

The learning activities are thus central in Biggs' model. A student undertakes activities in order to acquire the specified learning outcomes. The role of a curriculum and course developer, or a teacher is to create a learning environment that makes a student to engage in those learning activities that will lead to the desired learning outcomes. The educator's role is mainly to prepare a suitable teaching context (Biggs 1999).

The 3P-model describes teaching as a balanced system. All components of the teaching and learning system support each other. To work properly, all these components are aligned towards clearly defined learning outcomes. In Section 6.2, I operationalised the learning outcomes by defining, boundary crossing skills. Below I will elaborate heuristic principles for 'learning activities' and the 'teaching context'. These principles are summarized in Box 6.1.

Learning activities

What emerged from Chapters 2-5 is that a combination of experience in concrete interdisciplinary or transdisciplinary projects, close interaction and debate with persons with other scientific or cultural backgrounds and interests, theory training and explicit moments of reflection all contribute to learning boundary crossing skills.

Obtaining concrete experience in addressing a complex environmental problem and doing an interdisciplinary or transdisciplinary project is an excellent starting point. Going through all the stages of an interdisciplinary or transdisciplinary project, having to deal with incomplete data, addressing uncertainty and complexity, contribute to acquiring boundary crossing

(Chapter 2) and reflexive skills specifically (Chapter 5). Applying ESA procedures, methods and tools enhances interdisciplinary and transdisciplinary cognitive skills in particular (Chapter 4). Key elements for successfully structuring such an interdisciplinary or transdisciplinary project include: establish an accountability strategy; develop formal and informal communication strategies; address temporal and spatial scale issues; emphasize problem definition and team writing, and identify mentors (Chapter 2).

Switching perspective (as done with the matrix approach as explained in Chapter 2) and fieldwork both enhance the acquisition of boundary crossing skills. Switching perspectives involves working as a disciplinary expert, integrating disciplinary knowledge and empathizing with non-academic stakeholders. Fieldwork provides students with an opportunity to do so by experiencing the ‘complexity of reality’ to interact and empathize with local stakeholders. It provides them a context in which they can integrate theoretical knowledge, transcend disciplinary knowledge and combine and connect class-based knowledge with local knowledge from non-academic stakeholder. Furthermore, when fieldwork is combined with working and living abroad together (as was accomplished in the European Workshop of Wageningen University), it provides plenty of opportunities for discussion, reflection and amazements among students, teachers and other stakeholders on the available customs, approaches and expertise (Chapters 2 and 5). This experience and recognition of how cultural diversity influences research is also important.

Intensive group interaction, in particular in a team of which its members have diverse disciplinary and cultural backgrounds, confronts students with various disciplinary and cultural perspectives, and provides them with new insights that may not have emerged otherwise (Chapter 2). Team collaboration and interacting with stakeholders outside academia also trigger reflection. When the differences between the available scientific fields are sufficiently large, students become aware of differences in disciplinary approaches, perspectives, norms and values which all contribute to learning reflexive skills (Chapter 5). As explained before, this is a crucial component of boundary crossing skills.

Forcing students to switch perspectives, field work and intensive group interaction in an interdisciplinary or transdisciplinary project thus contribute to enhancing students’ awareness of disciplinary and cultural boundaries. They also likely add to the students’ appreciation of using different disciplinary and cultural perspectives in addressing complex environmental problems, because students realize that they themselves might only see a part of a bigger picture (Chapter 2). The students can be expected to develop a positive attitude or *habitus* to crossing boundaries, a precondition for being able to cross them (Section 6.2). Moreover, by working on a real project in an intercultural setting, students are confronted with shortcomings of scientific research and the often politicised nature of environmental management. Learning to cope with these issues by questioning the reliability of information and realising that decisions are often made in a particular context, expose students to the central challenges of crossing boundaries between theory and practice, disciplines and cultures (Chapter 2).

Notwithstanding the importance of experience in interdisciplinary or transdisciplinary projects and interaction with others, such experience alone seems insufficient to acquire boundary crossing skills. Students need theoretical training, and they need to be stimulated to reflect. Moreover, the experience need to be embedded in a suitable teaching context.

The teaching context

Mastering boundary crossing skills is a long-term process and requires attention throughout an environmental science curriculum. One individual course does not suffice to fully master these skills. Moreover, a curriculum that aims to train boundary crossing skills is a curriculum that safeguards disciplinary grounding. The importance of disciplinary knowledge became clear in the operationalisation of cognitive interdisciplinary and transdisciplinary skills (Section 6.2). In order to identify, understand, critically appraise and connect disciplinary theories, methodologies, examples and findings to address an environmental problem a student needs to have sufficient disciplinary knowledge. However, a curriculum that consists of various disciplinary courses, risks lack of coherence and focus. I showed that conceptual models, in particular domain models, can help to mitigate these risks and to structure an environmental science curriculum (Section 6.3). Moreover, domain models, such as the DPSIR model and the MA framework, can be used in an individual course as an example of applying a framework to integrate divergent knowledge (Chapter 3 and Section 6.3).

I also showed that students need theoretical training and that they need to be stimulated to reflect. Theory input consists of integrative ESA methods, models and tools (Section 6.4).

Theory also consists of the theoretical and philosophical aspects related to problem oriented environmental research, such as insights about science-society interactions in interdisciplinary and transdisciplinary research, the differences in logic of societal and scientific practices, and the role of perspectives and values in scientific research. Providing students with these latter insights is particularly important in training the students' reflexive skills (Chapter 5). Conceptual models, such as the van Koppen and Blom (1986) model and the Jahn (2008) model that schematise the research process, are very helpful in such training (Chapters 3 and 5). Such a model can be used as a reference to analyse and discuss the role of science in solving environmental problems and the contributions of various disciplines to tackle environmental issues.

As explained above, key in an environmental science curriculum that aims to train boundary crossing skills, is a course that enables a student to do an interdisciplinary or transdisciplinary project, to interact with persons (students, non-academic stakeholders and experts) with other scientific or cultural backgrounds and interests, and to switch perspective. The teacher's role in such a course differs considerably to traditional lecturing and providing information. Three crucial tasks for teachers in interdisciplinary or transdisciplinary student projects are disclosed: (i) facilitating the students' (research) experience, (ii) proving theory input, and (iii) encouraging students to reflect.

The facilitating role of teachers comprises making students aware of the various steps in a research project and helping them to take the next step. It comprises also of assisting the students' team work, identifying group leaders and encouraging those who are less vocal. The teachers' role is to help students to make decisions and to stimulate them to think critically by asking questions and providing tools rather than telling them exactly what to do. Their role is to provide feedback and encourage students to look critically at each other's work and learn from it. Yet, teachers need on the one hand to balance between providing a challenging environment, encouraging the students to take decisions and responsibility for their work, while on the other hand to ensure that all the tasks do not overwhelm the students (Chapters 2 and 5).

Facilitation by the teachers also encompasses stimulating students to switch perspectives, ensuring that students use their disciplinary knowledge and skills in an interdisciplinary research project, yet helping them to overcome disciplinary barriers and to improve integration in the overall project. Teachers thus play an important role in safeguarding disciplinary grounding while facilitating common grounding in an interdisciplinary project.

Finally, teachers can help students to reflect on the various epistemologies and norms and values (their own and those of others) that enter interdisciplinary and transdisciplinary research. They can do so by providing theory input related to problem oriented environmental science research. Teachers can also stimulate students to reflect critically on their experiences by using various conceptual models (Chapter 3), by actively scaffolding (Chapter 5) and by developing reflection assignments (Chapters 2, 4 and 5). Such reflection assignments can then be used to qualitatively assess students' boundary crossing skills (Chapters 2, 4 and 5).

6.6 Concluding remarks

With the map of boundary crossings skills (Figure 6.1) and the heuristic principles for teaching and learning them (Box 6.1), I contributed to a framework for educating environmental science students to address complex environmental problems. The previous chapters presented various examples of how these principles can be implemented in the educational context. I showed that mastering boundary crossing skills is a long term process and requires alignment of modules and courses of an environmental science curriculum. Careful curriculum planning is needed to safeguard sufficient disciplinary grounding and to prevent a superficial hodgepodge of disciplinary perspectives.

As clarified in this thesis all components of the teaching and learning system need to support each other. Not only the curriculum and its teaching methods, but also the assessment procedure, the climate created in interaction with the students, the institutional settings, and the rules and procedures need to be aligned. They all need to work together towards boundary crossing skills. Only under such conditions, can students effectively acquire and develop the necessary boundary crossing skills, required to successfully address the major environmental and sustainability challenges. A university that promotes 'Science for Impact' thus seems to be a suitable place to teach and learn boundary crossing skills.

Box 6.1: Heuristics principles for teaching and learning boundary crossing skills in environmental science education

Boundary crossing skills require:

The teaching and learning system

(1) A teaching and learning system that is aligned, i.e. the curriculum, the teaching methods, the assessment procedure, the climate created in interaction with the students and the institutional climate should all work together towards the learning outcomes, boundary crossing skills.
(2) Clearly defined and operationalized boundary crossing skills (see Figure 6.1).

Concerning 'learning activities' (i.e. what a student does)

(3) Experience, being involved in addressing a real-life complex environmental problem and applying disciplinary and interdisciplinary methods and techniques and procedures (e.g., derived from environmental systems analysis) to integrate solution-oriented knowledge.
(4) Close collaboration in a team of which its members have a diverse disciplinary and cultural background.
(5) Explicit moments of perspective switching (e.g., specialist, integrator, stakeholder).
(6) Field work, to integrate classroom-based knowledge in a specific context, to transcend disciplinary knowledge, and to experience the 'complexity' of reality.
(7) Interaction with stakeholders outside academia and facing the differences in norms and values held by the societal actors and oneself.
(8) Reflection on the research process, the role of science and the role of norms and values in addressing a societal problem.

Concerning the 'teaching context'

(9) Attention throughout an environmental science curriculum (mastering boundary crossing skills is a long-term process).
(10) A curriculum that safeguards disciplinary grounding.
(11) A coherent and focused curriculum for instance supported by simple, generic conceptual (domain) models.
(12) The use of both domain models and process models to illustrate the complexity of environmental problems, the integration of knowledge and the role of academic and non-academic knowledge, and of norms and values in addressing these problems.
(13) Theory input, such as tools, methods, and models from environmental systems analysis.
(14) Theory input and scaffolding by teachers who are able to reflect themselves on science-society interactions in interdisciplinary and transdisciplinary research, the differences in logic of societal and scientific practices and the role of values in scientific research.

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Appendix: Supplementary material for Chapter 5

S1 Final reflection report (1000 - 2000 words)

17 April 2013

The final reflection paper has to be based on your experiences throughout the whole EUW and it has to address your learning outcomes. Write a reflection paper of 1000 – 2000 words and use examples to illustrate your reflection wherever possible. For instance, describe an incident that made an impression on you (what happened), explain what your role was in the incident (what you did) and, finally, what you learned from it. Post this final reflection paper in the reflection drop box on SharePoint before 8 July 9.00h.

In your reflection distinguish again between: (i) the research project; (ii) group management and group dynamics; and (iii) your personal contribution.

(i): Reflection on the research project (max 1000 words)

Please consider the issues mentioned in the introduction and address the following questions in your reflection on the research project.

- In your opinion what kind of knowledge (scientific knowledge, knowledge from the area or knowledge held by stakeholders) did the EUW project group as a whole need to fulfil the requirements of the commissioner? Please elaborate on the importance of the type(s) of knowledge and indicate whether specific knowledge was lacking.
- In your opinion what did the EUW project contribute to the problem of the commissioner?
- The matrix approach of the EUW exemplifies an interdisciplinary approach to research. What is your opinion about the value of the interdisciplinary approach of the EUW? What kind of challenges did you experience throughout the research project in relation to the process of integrating theories, methodologies or data from different disciplines?
- Did values or interests influence the EUW research? If so, whose, which ones and when? Please elaborate and consider the various stages of the project: (i) problem orientation and problem framing; (ii) developing the methodology and data collection methods; (iii) data collection; (iv) data analysis; (v) reporting. Did values or interests influence the design of solutions or recommendations? Please give examples from the synthesis report.
- Please explain whether you fulfilled the learning outcome you set for yourself in your expectation paper (state your learning outcome again!).

(ii): Reflection on group management and group dynamics (max 500 words)

Please consider the issues mentioned in the introduction and address the following questions in your reflection on the group management and group dynamics:

- What role did the various planning and management tools play in the EUW? Were they useful or not?

- Please explain whether you fulfilled the learning outcome you set for yourself in your expectation paper (state your learning outcome again!).

(iii): Reflection on the personal level (max 500 words)

Please consider the issues mentioned in the introduction and address the following questions in your reflection on the personal level:

- In your opinion what kind of expertise (disciplinary and interdisciplinary scientific knowledge and academic skills) did you contribute to the EUW project and the problem of the commissioner? What kind of expertise did you acquire?
- What kind of challenges did you experience throughout the research project in contributing your expertise to the project? Did you experience differences in perspectives to the problem among participants of the course? If so, how did you respond to this?
- How did you personally deal with the group process: think about your own role, how you negotiated with others and the way decisions were made;
- What is your personal view on the problem you investigated and the best solutions to this problem? Did your view played a role in the way the group dealt with values and interests in the EUW research as discussed under (i)?
- Please explain whether you fulfilled the learning outcome you set for yourself in your expectation paper in relation to your personal contribution (state your learning outcomes again!).

S2 Rubric for reflection paper

	Points				
	0	1	2	3	4
Research project ("It")	Reflection on the research project is absent	Experience of the research project is merely described, with little attempt at reflection.	Experience of the research project is described clearly, with some specific examples. There is a clear attempt at reflection, but it may be superficial or only cover some of the elements requested (knowledge, contribution to the problem, interdisciplinarity, influence of values/interests).	Experience of the research project is described clearly and concisely, with specific examples. Reflection is adequate and covers most of the elements requested (knowledge, contribution to the problem, interdisciplinarity, influence of values/interests).	Experience of the research project is described clearly and concisely, with specific examples. Reflection is excellent and covers all the elements requested (knowledge, contribution to the problem, interdisciplinarity, influence of values/interests). It is clear what the student has learnt from the project and how s/he can use this in future projects.
Group work ("We")	Reflection on working as part of a group is absent.	Experience of working as part of a group is merely described. There is some attempt at analysis, but this stops at the evaluation stage and may be limited to the rest of the group. Specific examples are generally lacking.	Experience of working as part of a group is described clearly. There is some attempt at analysis, but this may be limited to the rest of the group. Some specific examples are given.	Experience of working as part of a group is described clearly and concisely. Personal experience of working as part of a group is analysed to gain a better understanding of self and others, but the analysis lacks depth. Reflection is illustrated by specific examples.	Experience of working as part of a group is described clearly and concisely. Personal experience of working as part of a group is analysed (evaluation of difficulties encountered, reflection about solutions which were/could have been applied) to gain a better understanding of self, others and group dynamics. Reflection is illustrated by specific examples.
Personal role ("I")	Student's role is unclear or lost in a lengthy, general description of the project. The text is entirely descriptive, with little or no attempt at analysis.	Student's role is merely described or a general description of the project is given. There is some attempt at analysis, but this stops at the evaluation stage. Specific examples are generally lacking.	Student's role is described clearly. There is an attempt to analyse personal experiences during the course, but this often stops at the evaluation stage and reflection is lacking. Some specific examples are given.	Student's role is described fairly concisely. Personal experiences during the course are analysed to gain a better understanding of self, but the analysis lacks depth. Reflection is illustrated by specific examples.	Student's role is described concisely. Personal experiences during the course are analysed (evaluation of difficulties encountered, reflection about solutions which were/could have been applied) to gain a better understanding of self. Reflection is illustrated by specific examples.
Learning goals: quality	Learning goals are impersonal (e.g. copied from the course goals), vague, unclear or non-existent.	Learning goals are fairly well-defined and personal, but are "safe", i.e. can easily be achieved just by attending the course. They do not encompass 'I', 'we' and 'it'.	Learning goals are clearly-defined and personal, though they are "safe", i.e. can easily be achieved just by attending the course. They encompass 'I', 'we' and 'it'.	Learning goals are clearly-defined, personal and ambitious, i.e. the student has to put in extra effort or move out of his/her comfort zone to achieve them. They encompass 'I', 'we' and 'it'.	
Learning goals: achievement	It is unclear whether the learning goals have been reached or not.	Outcome of the learning goals is mentioned but not how they were reached (or if not, why).	Outcome of the learning goals is mentioned, with some indication of how they were reached (or if not, why).	Outcome of the learning goals is mentioned, with clear indication of how they were reached (or if not, why).	Outcome of the learning goals is mentioned, with clear indication of how they were reached (or if not, why). Additionally, there is a reflection on the learning process involved and, if relevant, on ways to reinforce the knowledge/competences acquired or take them to the next level.
Structure	Structure is unclear and illogical. Text is rambling and disorganised with little or no attempt at paragraph construction.	Structure is unclear or illogical. Text is poorly organised with paragraphs which are too long or contain sudden changes of subject.	Structure is mostly clear and logical. Text is well organised with good paragraph construction.	Structure is clear and logical. Text is concise and well organised with excellent paragraph construction.	
English/clarity	English is poor, to the point where it hinders communication.	English is acceptable. The student manages to communicate effectively despite grammar/spelling mistakes.	English is good. The text is clear and reads well though there may be a few mistakes.		

S3 Questionnaire with reflexivity scores

Statement*)	Disagree 1	2	Agree 3	4	No opinion
1. Social values and political views play a role in every scientific research project.	0	0	1	2	0
2. In the nature area of the Veluwe, wild boars are hunted to reduce their number and to prevent that the animals go foraging and destroy the gardens in surrounding villages. There is, however, a heated debate between groups in favour of this hunting policy and groups that think the policy violates animal welfare. To analyse this problem, ecology is the key discipline.	2	1	0	0	0
3. In order to improve the sustainability of a city knowledge provided by scientists is more important than knowledge provided by non-academic stakeholders, such as civic associations or environmental non-governmental organisation.	2	2	1	0	0
4. When a team of scientists aims to address an environmental issue the disciplinary composition of the team influences the outcome of the study.	0	0	1	2	0
5. The main problem of transdisciplinary research is to get commitment from the stakeholder representatives.	2	2	1	0	0
6. The best way to do research that is useful to all stakeholder groups, is to remain objective and not include any values in research.	2	2	1	0	0
7. Wageningen Municipality aims to become a CO2 neutral municipality. In this context scientific research can provide an answer to the question: 'How should Wageningen Municipality increase the use of solar panels?'	2	1	0	0	0
11. Consider the following case: In a country there is a controversy over the location of a soil decontamination plant. A possible option is a low-income city. The decision could have effect on public health and on the local economy. Environmental scientists are able to solve this controversy by determining the potential health effects of the soil decontamination plant.	2	2	1	1	0
14. Recommendations to solve an environmental problem that are based on good scientific research are always objective.	2	1	0	0	0
16. When scientific research aims to address an environmental problem the scientists involved should be aware of interests of individuals or institutions that might influence the research.	0	0	1	2	0
17. The research objective of a research project that aims to address an environmental problem in a particular municipality should be negotiated between the scientists and stakeholders in the municipality.	0	1	2	2	0
18. Consider the following conclusion: "Our research provides evidence that for a robust population of the otter, the wetland size has to be doubled. Therefore, our research proofs that a larger area has to be designated as wetland reserve." Provided that the evidence is solid, this is a sound and objective scientific conclusion.	2	1	0	0	0
20. Knowledge from stakeholders such as governmental organisations and non-governmental organisations is interesting but not relevant for solving an environmental problem because it is very subjective.	2	1	0	0	0
21. In considering the societal impact of a research project, next to the research outcome the research process is important.	0	0	1	2	0
23. If two different scientists based on their research come to different conclusions on how to address a particular environmental problem, at least one of them did a bad job in his/her research.	2	2	1	0	0
24. As a scientist I have to be aware of my own opinion and interests, because they might influence my research.	0	0	1	2	0
25. In environmental research it is important to reflect on the role of stakeholders and their values.	0	0	1	2	0

The statements 1, 2, 10, 12, 13, 15, 19 and 22 are not shown because they were not included in the analysis.

S4 Results Wilcoxon signed rank test comparing the reflexivity score of the pre- and post-test

Participated in:		N	Mean Rank	Sum of Ranks	Z	Asymp. Sig (1-tailed)
					Test-statistics	
EUW-Brno	Negative ranks	12	10.38	124.5		
	Positive ranks	10	12.85	128.5		
	Ties	4				
	Total	*26*			*-0.65*	*0.474*
EUW-Budapest	Negative ranks	8	10.25	82		
	Positive ranks	17	14.29	243		
	Ties	4				
	Total	*29*			*-2.181*	*0.0145*
EUW-Fosen	Negative ranks	8	10.13	81		
	Positive ranks	16	13.69	219		
	Ties	3				
	Total	*27*			*-1.974*	*0.024*
EUW-Total	Negative ranks	28	30.63	857.5		
	Positive ranks	43	39.50	1998.5		
	Ties	11				
	Total	*82*			*-2.416*	*0.008*

- Negative ranks: RS(Si) post-test < RS(Si) pre-test;
- Positive ranks: RS(Si) post-test > RS(Si) pre-test;
- Ties: RS(Si) post-test = RS(Si) pre-test
- Z is based on negative ranks

Summary

Since the 1970s academic environmental science curricula have emerged all over the world addressing a wide range of topics and using knowledge from various disciplines. These curricula aim to deliver graduates with competencies to study, understand and address complex environmental problems. Complex environmental problems span broad spatial, temporal and organisational scales, are multi-dimensional and involve political controversies. They are further characterized by many uncertainties and conflicting views on the nature of the problem and the best way to solve them. Generally accepted frameworks to educate environmental science graduates with the necessary competencies to address complex environmental problems are scarce. With this thesis, I aimed to explore and develop heuristic principles (i.e. 'rules of thumb') for teaching and learning activities that enable environmental science students to especially acquire boundary crossing skills. These skills are needed to develop sustainable solutions for complex environmental problems. I focussed on interdisciplinary and transdisciplinary cognitive skills as a sub-set of boundary crossing skills, and on the potential contribution of conceptual models and environmental systems analysis in teaching and learning these skills.

In order to achieve this aim, I did four studies (see Chapters 2 - 5). These studies were based on an extensive literature review, analysis of existing courses and course material at Wageningen University and elsewhere, personal experience and analysis of reflection papers written by students in authentic learning settings. The last study (Chapter 5) was an empirical statistical study. Here, I developed a strategy for teaching and learning reflexive skills, a subcomponent of interdisciplinary and transdisciplinary cognitive skills, and evaluated this strategy in a quasi-experimental setting.

The studies showed that operationalizing skills and developing teaching and learning activities are closely intertwined. Below, first boundary crossing skills are explicated. Next, the contribution of conceptual models and environmental systems analysis to develop interdisciplinary and transdisciplinary cognitive skills, specifically, is explained. Finally, heuristic principles for teaching and learning activities to develop boundary crossing skills are presented.

Boundary crossing skills in environmental science education

To understand complex environmental problems and develop sustainable solutions require skills to cross boundaries between disciplines, between cultures and between theoretical knowledge and practice. In this study, I used the concept of skills in a broad sense that included not only the actual skills of using different perspectives and dealing with the complexities and uncertainties involved, but also the knowledge (e.g., being aware of various perspectives) and the attitudes (e.g., toward using these perspectives) which are vital for these skills.

Interdisciplinary and transdisciplinary cognitive skills enable a person to integrate knowledge and modes of thinking in two or more disciplines to produce a cognitive advancement (e.g., solving a problem). I identified three components of these skills. The first component skill is the ability to understand environmental issues in a holistic way (i.e. considering different perspectives, systemic social and biophysical elements and their dynamics and interactions). The ability to frame environmental problems holistically allows a comprehensive insight into all relevant aspects to possibly solve the studied problem. The second component skill is the ability to identify, understand, critically appraise and connect disciplinary theories, methodologies, examples and findings into the integrative frameworks required to analyse environmental problems and to devise possible solutions. The third component skill is the ability to reflect on the role of disciplinary, interdisciplinary and transdisciplinary research in solving societal problems. The third component skill is about critically assessing the role of science in society. It encompasses reflecting on the processes of knowledge production and application. I introduced the term “reflexive skills” for this third component.

Furthermore, I distinguished two sub-components of reflexive skills: (i) the ability to assess the relative contributions of scientific disciplines and non-academic knowledge in addressing environmental issues; and (ii) the ability to understand the role of norms and values in problem-oriented research.

The contributions of conceptual models to teach and learn boundary crossing skills

My research showed that conceptual models are useful tools, for teachers, course and curriculum developers, and students, to cope with the challenges of environmental sciences (Chapter 3). These challenges are inherent to the interdisciplinary and problem-oriented character of environmental sciences curricula. The first challenge concerns the structure of a curriculum (i.e. how does one design a coherent curriculum, while including various disciplines?). The second challenge is teaching integrated problem-solving.

I introduced two types of conceptual models: domain models and process models. Domain models structure the domain of environmental sciences. Process models depict the different steps in an environmental research process and clarify how these steps are related to societal processes important to the research. Both types of models are valuable because they can be used to (i) improve the coherence and focus of an environmental sciences curriculum; (ii) analyse environmental issues and integrate knowledge; (iii) examine and guide the process of environmental research and problem solving; and (iv) examine and guide the integration of knowledge in the environmental-research and problem-solving processes (Chapter 3).

To expose students to a range of conceptual models during their education is essential, because such a variety is instrumental in enhancing the students' awareness of the various approaches to frame environmental issues and to illustrate and explain how this framing has changed over time or what its consequences are. By applying and reflecting on these conceptual models, students likely acknowledge the complexity of human-environment systems and science's role in dealing with complex environmental problems (Chapter 3).

Environmental systems analysis's contribution to teach and learn boundary crossing skills

My research demonstrated that education in environmental systems analysis (ESA) improves students' knowledge about integrative tools, techniques and methodologies, and their application, but also – to a certain extent – their interdisciplinary and transdisciplinary cognitive skills (Chapter 4). ESA education helps to conceptualize and frame an environmental issue holistically (i.e. first component cognitive skill). By applying ESA tools, methods and models to environmental problems, students become aware of the broader context of an environmental problem, its direct and indirect causes, and its direct and indirect effects, the probable connections between local and global issues, and the interactions with various societal actors and stakeholders. ESA education likely enhances students' ability to identify and connect disciplinary approaches in integrative frameworks, but only enhances the students' ability to critically appraise disciplinary approaches in integrative frameworks (i.e. second component cognitive skills) to some extent. In order to be able to appraise the contribution of such a disciplinary approach to a specific environmental problem, students need to have sufficient disciplinary knowledge and disciplinary education is needed. ESA education likely supports the ability to critically reflect on the role of disciplinary and interdisciplinary research in solving societal problems (i.e. the third component cognitive skills) by making students aware that a system always represents a simplified model and a particular perspective of reality, but more is needed. To successfully train students' reflexive skills, specific teaching and learning activities are needed (Chapter 4). These are addressed hereafter.

Heuristics principles to teach and learn boundary crossing skills in environmental science education

My research revealed that acquiring boundary crossing skills requires learning activities that involve a combination of experience in concrete interdisciplinary or transdisciplinary projects, close interaction and debate with persons with other scientific or cultural backgrounds and interests, theory training and explicit moments of reflection. Obtaining concrete experience in addressing a complex environmental problem and developing and executing an interdisciplinary or transdisciplinary project is an excellent starting point. Going through all the stages of an interdisciplinary or transdisciplinary project, having to deal with incomplete data, addressing uncertainty and complexity, contribute to acquiring boundary crossing (Chapter 2) and reflexive skills, specifically (Chapter 5). Switching perspective, fieldwork and intensive group interaction enhance the acquisition of boundary crossing skills (Chapters 2 and 5). Switching perspectives involves working as a disciplinary expert, integrating disciplinary knowledge and empathizing with non-academic stakeholders. Fieldwork provides students with an opportunity to do so by experiencing the 'complexity of reality' to interact and empathize with local stakeholders. Intensive group interaction, in particular in a team whose members have diverse disciplinary and cultural backgrounds, makes students aware of differences in disciplinary approaches, perspectives, norms and values. This also contributes to a positive attitude or *habitus* to crossing boundaries, which is a precondition for being able to cross them (Chapters 2 and 4). I showed that notwithstanding the importance of experience in interdisciplinary or transdisciplinary projects and interaction with others, such experience alone seems insufficient to acquire boundary crossing skills. Students need theoretical training and they need to be stimulated to reflect (Chapter 5).

Key in an environmental science curriculum that aims to train boundary crossing skills, is thus a course that enables a student to actively involve in an interdisciplinary or transdisciplinary project, to interact with persons (students, non-academic stakeholders and experts) with other scientific or cultural backgrounds and interests, and to switch perspective. The teacher's role in such a course differs considerably to traditional lecturing and providing information. I disclosed three crucial tasks for teachers in interdisciplinary or transdisciplinary student projects: (i) facilitating the students' (research) experience, (ii) proving theory input, and (iii) encouraging students to reflect.

Theory input consists of integrative ESA methods, models and tools (Chapter 4). Theory also consists of the theoretical and philosophical aspects related to problem oriented environmental research, such as insights about science-society interactions in interdisciplinary and transdisciplinary research, the differences in logic of societal and scientific practices, and the role of perspectives and values in scientific research (Chapter 3). Providing students with these latter insights is particularly important in training the students' in reflexive skills (Chapter 5).

Mastering boundary crossing skills is a long term process and requires alignment of modules and courses of an environmental science curriculum. Not only the teaching methods, but also the assessment procedure, the climate created in interaction with the students, the institutional settings, and the rules and procedures all need to work together towards boundary crossing skills as learning outcomes. Only under such conditions, can students effectively acquire and develop the necessary boundary crossing skills, required to successfully address the major environmental and sustainability challenges.

Nederlandse samenvatting

Complexe milieuvraagstukken omvatten verschillende schaalniveaus van tijd, plaats en organisatie, zijn multidimensionaal en politiek controversieel. Ze worden verder gekenmerkt door vele onzekerheden en conflicterende visies op wat het probleem is en wat de beste manier is om het probleem aan te pakken. Al veertig jaar streven opleidingen in de milieuwetenschappen er naar afgestudeerden af te leveren met vaardigheden om milieuproblemen te bestuderen, te begrijpen en te helpen oplossen. Desondanks zijn algemene richtlijnen voor het leren van de noodzakelijke vaardigheden om complexe milieuvraagstukken te helpen oplossen schaars. Doel van deze thesis was het exploreren en ontwikkelen van een aantal vuistregels (*heuristic principles*) voor onderwijs- en leeractiviteiten waarmee milieustudenten deze vaardigheden kunnen verwerven. In deze thesis wordt gebruik gemaakt van de term *boundary crossing skills*. Door het overbruggen (*crossing*) van grenzen (*boundaries*) tussen disciplines, tussen culturen, en tussen theorie en praktijk kunnen complexe milieuproblemen beter worden begrepen en duurzame oplossingen ontworpen. De thesis focust op de bijdrage van conceptuele modellen en milieusysteemanalyse aan het leren van cognitieve vaardigheden.

Om vuistregels te ontwikkelen heb ik vier studies gedaan. Deze studies zijn gebaseerd op literatuuronderzoek, analyse van bestaande cursussen en cursusmateriaal van Wageningen Universiteit en elders, persoonlijke ervaring en analyse van reflectieverslagen geschreven door studenten in een authentieke leeromgeving. De laatste studie was een empirische. Ik heb een strategie ontwikkeld voor het leren van reflexieve vaardigheden, een onderdeel van boundary crossing skills. Vervolgens heb ik deze strategie geëvalueerd in een quasi-experimentele setting.

Hieronder zal ik eerst boundary crossing skills specificeren. Vervolgens zal ik de bijdrage die conceptuele modellen en milieusysteemanalyse kunnen leveren aan het leren van deze vaardigheden toelichten. Tot slot zal ik de vuistregels voor onderwijs- en leeractiviteiten presenteren.

Boundary crossing skills in het onderwijs in de milieuwetenschappen

Deze thesis focust op inter- en transdisciplinaire cognitieve vaardigheden, een deelverzameling van boundary crossing skills. Inter- en transdisciplinaire cognitieve vaardigheden stellen een persoon in staat om kennis en manieren van denken vanuit twee of meer disciplines te integreren en een cognitieve vooruitgang te boeken, zoals bij het oplossen van een probleem. In deze thesis heb ik het begrip vaardigheden (*skills*) in brede zin gebruikt. Deze skills omvatten niet alleen de werkelijke vaardigheden, zoals het integreren van verschillende perspectieven en het omgaan met complexiteit en met onzekerheden; ze omvatten ook kennis (bijvoorbeeld het zich bewust zijn van verschillende perspectieven) en houding (bijvoorbeeld tegenover het gebruik van deze perspectieven) die essentieel zijn voor deze vaardigheden.

Binnen de inter- en transdisciplinaire cognitieve vaardigheden heb ik drie componenten onderscheiden. De eerste component is het vermogen milieuvraagstukken te begrijpen op een holistische manier, dat wil zeggen rekening houdend met verschillende perspectieven op het probleem. Dit vermogen stelt een persoon in staat om alle relevante aspecten mee te nemen in het ontwerpen van een mogelijke oplossing. De tweede component is het vermogen om disciplinaire theorieën, methodologieën, voorbeelden en bevindingen te identificeren, te begrijpen, kritisch te beoordelen en te verbinden in een integraal raamwerk dat nodig is om een milieuvraagstuk te analyseren en een oplossing te ontwerpen. De derde component is het vermogen tot kritische reflectie op de rol van wetenschap in de maatschappij. Het behelst het reflecteren op het proces van kennisproductie en toepassing. Voor deze derde component heb ik de term reflexieve vaardigheden (*reflexive skills*) geïntroduceerd. Deze reflexieve vaardigheden kunnen weer worden opgedeeld in: (i) het vermogen om de relatieve bijdrage van wetenschappelijke disciplines en niet-academische kennis in het aanpakken van milieuvraagstukken kritisch te beschouwen; (ii) het vermogen om de rol van waarden en normen in probleemgericht onderzoek te begrijpen.

Conceptuele modellen en het leren van boundary crossing skills

Mijn onderzoek wees uit dat conceptuele modellen zeer geschikt zijn voor het structureren van een milieucurriculum en voor het leren van probleemoplossen op een geïntegreerde manier. Twee typen conceptuele modellen heb ik onderscheiden: domeinmodellen en procesmodellen. Domeinmodellen structureren het domein van de milieuwetenschappen. Procesmodellen illustreren de verschillende stappen in het proces van een milieuonderzoek en maken duidelijk hoe deze stappen zijn gerelateerd aan maatschappelijke processen die van belang zijn voor dit onderzoek. Beide typen modellen zijn waardevol voor milieuonderwijs, omdat ze kunnen worden gebruikt om (i) de coherentie en focus van een curriculum in de milieuwetenschappen te verbeteren; (ii) een milieuvraagstuk te analyseren en kennis te integreren; (iii) het proces van milieuonderzoek en probleemoplossen te onderzoeken en te begeleiden; en (iv) de integratie van kennis in milieuonderzoek en probleemoplossen te onderzoeken en te begeleiden.

Het is belangrijk om milieustudenten kennis te laten maken met verschillende conceptuele modellen, omdat een verscheidenheid aan conceptuele modellen deze studenten bewust maakt van het feit dat er verschillende manieren zijn waarop een milieuvraagstuk kan worden beschouwd. Door verschillende modellen toe te passen en hierop te reflecteren, kunnen studenten de complexiteit van mens-milieusystemen en de rol van wetenschap in de aanpak van complexe milieuvraagstukken beter begrijpen.

Milieusysteemanalyse en het leren van boundary crossing skills

Mijn onderzoek liet zien dat onderwijs in milieusysteemanalyse (MSA) de kennis van integratieve methoden en technieken en hun toepassingen bij studenten vergroot, en dat het –tot op zekere hoogte– ook bijdraagt aan de drie componenten van inter- en transdisciplinaire cognitieve vaardigheden. MSA-onderwijs helpt studenten milieuvraagstukken te conceptualiseren op een holistische manier (eerste component). Door het toepassen van MSA-methoden, -technieken en -modellen op milieuvraagstukken worden studenten zich bewust van de bredere context van het milieuvraagstuk, de directe en indirecte oorzaken en de directe en indirecte effecten, de mogelijke relaties tussen lokale en globale aspecten en de interacties met verschillende maatschappelijke actoren. Daarnaast draagt MSA-onderwijs mogelijk bij aan het vermogen van een student om disciplinaire benaderingen te identificeren en te verbinden in een integratief raamwerk (tweede component). MSA-onderwijs draagt slechts gedeeltelijk bij aan het verbeteren van het vermogen van studenten om disciplinaire bijdragen kritisch te beoordelen. Om die disciplinaire bijdrage aan een specifiek milieuprobleem op waarde te schatten, hebben studenten voldoende disciplinaire kennis nodig en hiervoor is disciplinair onderwijs nodig. MSA-onderwijs kan bijdragen aan het vermogen om kritisch te reflecteren op de rol van disciplinair en interdisciplinair onderzoek in het oplossen van maatschappelijke vraagstukken (derde component), omdat MSA studenten duidelijk kan maken dat een systeem altijd een versimpeling van en een bepaald perspectief op de werkelijkheid is. Om reflexieve vaardigheden van studenten te trainen zijn echter specifieke onderwijs- en leeractiviteiten nodig.

Vuistregels voor onderwijs- en leeractiviteiten

Mijn onderzoek toonde aan dat voor het verwerven van boundary crossing skills een combinatie nodig is van ervaring in concrete inter- of transdisciplinaire projecten, nauwe interactie en discussie met mensen met andere wetenschappelijke of culturele achtergronden en belangen, theoretische input en expliciete momenten van reflectie. Het onderzoeken van een complex milieuvraagstuk en het doen van een inter- of transdisciplinair project is een uitstekend beginpunt. Het doorlopen van alle stappen van het project, het omgaan met incomplete data, onzekerheden en complexiteit, draagt bij aan het verwerven van boundary crossing skills en reflexieve skills in het bijzonder. Met name perspectiefwisseling, veldwerk en intensieve interactie met anderen draagt bij aan het leren van deze skills. Perspectiefwisseling houdt in het werken als een disciplinaire expert, het integreren van disciplinaire kennis en het inleven in niet-academische stakeholders. Veldwerk in een team van studenten biedt hen de mogelijkheid de complexiteit van de werkelijkheid te ervaren, van perspectief te wisselen en te interacteren met elkaar en met lokale stakeholders. Intensieve interactie, vooral in een team waarvan de leden diverse disciplinaire en culturele achtergronden hebben, maakt studenten bewust van de verschillende disciplinaire benaderingen, perspectieven, waarden en normen. Dit draagt bij aan een positieve houding om boundaries te overbruggen; een belangrijke vereiste om ze te kunnen overbruggen. Ervaring in inter- of transdisciplinaire projecten en interactie met anderen is dus zeer belangrijk. Deze ervaring alleen bleek echter onvoldoende voor het verkrijgen van reflexieve vaardigheden. Voor het verwerven van deze vaardigheden hebben studenten theoretische input nodig. Bovendien moeten ze worden gestimuleerd te reflecteren op hun ervaring. De rol van de docent is hierin essentieel.

Drie cruciale taken voor docenten in het begeleiden van inter- en transdisciplinaire studenten projecten heb ik geïdentificeerd: (i) het faciliteren van de (onderzoeks)ervaring van de studenten; (ii) het verschaffen van theoretische input; en (iii) het stimuleren van de studenten tot reflectie.

De theoretische input kan bestaan uit integratieve MSA-methoden, -technieken en modellen, maar zal ook moeten bestaan uit theoretische en filosofische aspecten van probleemgericht milieuonderzoek, zoals inzicht in de relatie wetenschap en maatschappij in inter- of transdisciplinair onderzoek, verschillen in de maatschappelijke en wetenschappelijke praktijk, en de rol van perspectieven en waarden en normen in wetenschappelijk onderzoek. Deze laatste inzichten zijn met name belangrijk voor het leren van reflexieve vaardigheden.

Het verwerven van boundary crossing skills is een langetermijnproces en vereist overeenstemming tussen modules en cursussen in een milieucurriculum. Bovendien zullen niet alleen de onderwijsmethoden, maar ook de beoordelingsprocedures, de interactie tussen docenten en studenten, de institutionele setting, regels en procedures moeten overeenstemmen en toewerken naar dezelfde leeruitkomsten: boundary crossing skills. Alleen onder dergelijke condities kunnen studenten effectief boundary crossing skills verwerven die nodig zijn om complexe milieu- en duurzaamheidsvraagstukken te helpen oplossen.

.

Dankwoord

Tien jaar geleden had ik me nog niet kunnen voorstellen dat ik ooit een proefschrift zou schrijven. Dankzij de stimulans van Kris, volledig ondersteund door Rik, ben ik het avontuur aangegaan. Kris, ik herinner me nog goed ons gesprek in de tuin van de Leeuwenborch, waarin je aanbood mij te begeleiden en waarin ik besloot met mijn PhD te beginnen. Enige tijd mocht ik op vrijdag gebruik maken van jouw kamer op milieubeleid om op die manier me fysiek te kunnen afzonderen van de Milieusysteemanalyse (MSA)-perikelen en me beter te kunnen concentreren op mijn onderzoek. Dit bleek zeker in de beginperiode essentieel. Het was niet altijd makkelijk om op mijn kamer op MSA te focussen, vooral omdat in die tijd studenten nog gewoon kwamen binnen wandelen als ze iets te vragen hadden. Maar veel belangrijker nog waren de vele discussies met jou de afgelopen jaren, soms via Skype, meestal op jouw kamer. Jouw kritische, maar altijd constructieve opmerkingen hebben mij enorm geholpen steeds weer een stapje verder te zetten en uiteindelijk dit project af te ronden. Ik dank je voor al die discussies de afgelopen jaren.

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About the author

Karen Fortuin was born in Sittard, the Netherlands on 8 September 1964. She graduated in Milieuhygiëne (Environmental Sciences) at Wageningen University in 1988 (majors Soil hygiene and pollution, and Environmental education and communication). During her studies she became very interested in education and in interdisciplinarity.

Her first job after graduation (1988-1991) was at the Zeeuwse Milieufederatie in Goes, where she worked as an environmental educator and staff member. From 1991 till 1993 she worked as a lecturer at the Hogeschool Rotterdam & Omstreken where she was involved in contract education in the field of environmental science for various target groups and in the organisation of an international conference on environmental education in Europe.

In 1993 she started as a lecturer at the Centre for Environmental Studies of Wageningen University, that later merged into the Centre for Environment and Climate Studies Wageningen. This centre was responsible for the coordination of interdisciplinary environmental science education and research at Wageningen University. Around 2000 the environmental science programs at Wageningen University drastically changed and a new chair group Environmental Systems Analysis was established. Karen joined this chair group.

Karen has developed and executed several BSc and MSc environmental science and environmental systems analysis courses. Besides she has been involved in various educational programs of Wageningen University. She was closely involved in the development of the BSc and MSc environmental sciences programs, first as a secretary (1998-2005) and later as a chair (2005-2008) of the Program Committee Environmental Sciences. She worked as a visiting scientist at the University of British Columbia, Canada (2005) and at the Swiss Federal Institute of Technology in Zurich, Switzerland (2009). In 2007 she decided to start her PhD on interdisciplinarity in environmental science education. While doing her PhD she continued her teaching activities facilitating a close interaction between her educational practice and research activities.

Karen Fortuin is married and has two sons of 13 and 17 years old.

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SENSE PhD Courses

- Research in Context Activity: Developing and delivering 'Seminar Interdisciplinarity in Scientific Research and Education', Wageningen University (2012)

Other PhD and Advanced MSc Courses

- Techniques for writing and presenting a scientific paper, Wageningen University (2008)
- Interdisciplinary and transdisciplinary research: intervision and communications skills, Wageningen University (2009)
- Reviewing a scientific paper, Wageningen University (2011)

External training at a foreign research institute

- Sabbatical to study the interdisciplinary graduate programme 'Resource Management and Environmental Studies', University of British Columbia, Canada (2005)
- Sabbatical to study the ETH-NSSI 'Transdisciplinary Case Study Approach' in the Department of Environmental Sciences, Swiss Federal Institute of Technology in Zurich (ETHZ), Switzerland (2009)

Management and Didactic Skills Training

- Secretary of Program Committee Environmental Sciences (1998-2005)
- Developing and executing various Environmental Systems Analysis BSc and MSc courses (1998-2015)
- Chair of Program Committee Environmental Sciences (2005-2008)
- Teaching in the International and Multicultural Classroom, Wageningen University (2013)
- Member of Program Committee Communication Sciences (2013-2015)

Selection of Oral Presentations

- *Cognitive skills in inter- and transdisciplinary projects: The role of education in environmental systems analysis.* International Transdisciplinarity Conference (td-net): 'Implementation in Inter- and Transdisciplinary Research, Practice and Teaching', 15-17 September 2010, Geneva, Switzerland
- *The value of a conceptual model of transdisciplinarity to enhance students' reflexivity; theory framework and experimental design.* Conference on Transdisciplinary Research and Modelling, 10-11 April 2013, Munich, Germany
- *Problem Based Learning to enhance students' reflexivity; theory framework and experimental design.* Engineering Education for Sustainable Development 2013: 'Rethinking the engineer', 22-25 September 2013, Cambridge, United Kingdom
- *The changing role of scientists.* SENSE Summer Symposium 2015: 'Make a change! - Successful interaction with society', 18 June 2015, Wageningen, The Netherlands

SENSE Coordinator PhD Education

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