1. General introduction
1.1 Introduction

Global change processes are having an enormous impact on the earth's natural resource base. The rate of biodiversity loss is unprecedented high: a quarter of the earth's estimated 100 million species on earth may have disappeared within less than 50 years if current rates continue (Ehrlich and Wilson, 1991; Koshland, 1991; Myers, 1997). Human induced increases in global atmospheric CO$_2$ and other greenhouse gases are causing a global warming of the earth’s atmosphere (Solomon et al., 2007). Human demand for scarce water resources is still increasing, and is expected to increase (Vörösmarty et al., 2000; Postel, 2000).

Political decision-makers are increasingly expected to create economic growth and development while minimizing the impact on the earth's natural resource base. As a result, they have to attempt to (re)direct these processes and developments with policy measures in the direction of sustainable growth. To make informed decisions, it is often necessary to assess potential policy measures and their effects beforehand (Sieber et al., 2010). Impact assessments are typically used for this. An impact assessment can best be characterized as “a process that prepares evidence for political decision-makers on the advantages and disadvantages of possible policy options by assessing their potential impacts” (Sieber et al., 2010). Impact assessments can be used to assess the effects on a range of topics. Amongst others, they can be used to assess the economic, social and environmental effects of policy measures (Easterling, 1997; Verburg et al., 2006). Impact assessments combining knowledge from a range of disciplines to evaluate an entire chain of causes-and-effects are often referred to as integrated assessment (Schneider, 1997; Van der Sluis, 2002). While recognizing that impact assessments can encompass a broad range of topics and forms, this thesis will focus exclusively on integrated environmental assessments.

Although integrated environmental assessments are often used, some authors argue that their effectiveness in supporting policy-making could be improved by giving more attention to processes operating at different scales. Current integrated environmental assessments are typically either very local (e.g. to obtain clearance for building or industrial development), or they have a focus on broad, macro-scale trends in which local differences and heterogeneity are not well represented (Easterling, 1997; Wilbanks and Kates, 1999; Cash and Moser, 2000; Rothman et al., 2009). By focusing on a single scale, integrated environmental assessments have a tendency to overestimate the importance of the processes functioning at this scale and rely heavily on datasets fitting this scale (Wilbanks and Kates, 1999; Cash and Moser, 2000). Thus often processes operating at a different scale and cross-scale in-
Interactions are not given sufficient attention in integrated environmental assessments. Moreover, global change processes themselves are often very complex and may involve non-linear relations, which makes their behaviour almost intrinsically unpredictable. Although they show a clear trend at an aggregated level, they can locally behave very differently due to non-linearity and local heterogeneity (Cash and Moser, 2000; Wilbanks, 2007). The intrinsic variability of these processes is an additional confounding factor in integrated environmental assessments and makes location-specific predictions in integrated environmental assessments very difficult. Several examples can be given of global change processes that have unforeseen and unexpected micro-scale level impacts. For instance, global deforestation is a trend which is especially strong in many developing countries, where vast expanses of tropical rainforest or savanna still exist in combination with weak economies, institutional incapacity, high urbanization rates, and increasing globalization (Lambin et al., 2001; Lambin et al., 2003). But this global trend of land use change does not apply to Europe where forest cover is actually increasing. In fact, many European regions face substantial land abandonment instead of deforestation due to agricultural intensification, technological advance, trade liberalization and policy incentives (the EU’s Common Agricultural Policy), resulting in less farm income on marginal farmland and subsequent abandonment of these lands (Verburg et al., 2008; MacDonald et al., 2000). Clearly, the global land use change trend of ever decreasing natural habitats has played out unexpectedly in Europe with an actually increasing forest cover. A similar observation can be made in the case of climate change; i.e. global temperatures are projected to increase but locally they might remain stable and comparable to current temperatures (Christensen et al., 2007). This variation is mainly driven by local differences in abiotic conditions (e.g. uneven distribution of global solar heating, differences in slope, aspect, relief, and distance to sea). However, some human-induced factors can also have a local influence on climatic conditions (e.g. local emissions of sulphate aerosols). Together with unexpected feedback processes and non-linear interdependencies, these local variations make that projected changes in climate vary from region to region (Christensen et al., 2007). Of course, this local variability makes it very hard to give predictions regarding the expected climate changes at a specific location as often it is needed to assess the local consequences and specific adaptation needs. Many other global change processes are equally complex as climate change, and representing them correctly at a finer scale in an integrated environmental assessment is equally challenging.

The bias on large scale processes and the limited ability to correctly represent these processes at a finer scale has several repercussions for the use of integrated environmental assessments. Firstly, the credibility of the applied (modelling) tools and the
integrated environmental assessment as a whole is often negatively affected when local conditions are poorly represented in the integrated environmental (Cash and Moser, 2000). Secondly, the urgency of a global change process is often not recognized by the public and policy makers when local conditions and impacts are not well represented and recognized in the integrated environmental assessment. Thirdly, local policy-makers have a strong need for knowledge regarding the local impacts of global change because adaptation measures often need to be taken at the local scale. The inability of integrated environmental assessments to adequately predict the impact of global change at individual locations therefore limits their usefulness for (local) policy makers (Cash and Moser, 2000). However, an exclusive focus on local scale impacts also has serious drawbacks. For instance, an overemphasis on the local cause-and-effects of a global change process can result in overlooking important global, large-scale developments that are important but more underlying (Wilbanks and Kates, 1999). This makes it impossible to derive more generic conclusions and also limits the value of the analysis in supporting policy decisions (Wilbanks, 2007). Moreover, the cause-and-effect chains of these processes are often more easily to structure and better to comprehend at a local scale (Wilbanks, 2007), which makes it tempting to go into too much detail. Up-scaling of results can then become extremely difficult as the level of complexity typically increases at a higher spatial scale, making the analysis (and its’ results) increasingly difficult to understand and apply for policy makers (Wilbanks, 2007). Especially policy makers at higher scales (e.g. national government) will have very little interest in such assessments that focus too much on local scale processes as they are more interested in the overall, aggregate impacts of a global change process (Cash and Moser, 2000). Therefore, integrated environmental assessments analysing global change processes and their impacts at both larger and smaller scale are most useful for policy support because they cater to the needs of policy makers at both higher and local scales (Wilbanks and Kates, 1999; Cash and Moser, 2000; Wilbanks, 2007; Rothman et al., 2009). However, methodologies to simultaneously analyse both scales in integrated environmental assessments are not yet fully developed and need improvement (Rothman et al., 2009). This chapter will first explain in more detail the various roles of integrated environmental assessments in supporting policy decisions and processes, and will then discuss the currently available modelling methodologies used in integrated environmental assessments. Finally this chapter will explain the main aim of this PhD-thesis, which is to find improvements in current integrated environmental assessment methodologies for analysing global change at multiple scales for better supporting policy making.
1.2 The role of integrated environmental assessment in policy processes

Policy is typically developed in a process of subsequent steps or phases (Vedung, 1997; Engels, 2005; Lee, 2006). Vedung (1997) describes these different steps in the policy cycle. First an issue is recognized and formulated by policy makers as a problem for which policy is needed (i.e. decision preparation phase; Vedung, 1997). Subsequently, a decision is made on how to solve the problem and appropriate targets are set (decision phase). Then the selected policy measures are implemented (implementation phase). After this, policy measures are monitored and their effectiveness assessed (evaluation phase). During this process, the original problem definition, targets and policy measures can shift and be adapted in a recursive process as a result of new insights and a changing (political) setting (feedback phase). This whole process is referred to as the policy cycle (Vedung 1997). Engels (2005) evaluates the policy cycle based on the opportunities in it for integrated environmental assessments to contribute to policy making, and discerns the following steps:

- **Scientific warning and awareness creation:**
  In this phase, policy makers are alerted on a potential problem and are pressured to recognize an issue as a problem for which policy is needed. Integrated environmental assessments do not typically play an important role in scientific...
warning and awareness creation. However, there are examples where integrated assessments have triggered awareness, e.g. in case of the Club of Rome integrated assessment models have triggered a lot of public awareness (Meadows et al., 1972) as well as in the debate on indirect land use effects of biofuel policies (Eickhout et al., 2007)

- **Problem definition:**
  In the decision preparation phase, scientific expertise is often required in defining the problem: i.e. the cause-effects of the issue need to be established based on available scientific information and a general consensus needs to be reached about this. Additionally, scientific expertise is needed to generate potential strategies to solve the problem (Vedung, 1997; Engels, 2005; Lee, 2006). Possible (environmental) side-effects of these strategies are not explicitly considered during problem definition (and during the decision preparation phase as a whole). Therefore, integrated environmental assessments are usually not used in this phase. But although integrated environmental assessments are typically used later in the policy cycle, some authors have suggested that they should actually be started up in this early phase (Sheate et al., 2003; Lee, 2006). They argue that policy makers have a tendency to already make some form of decision about the solution of the problem in this early phase by considering some potential solutions as (e.g. politically) unrealistic. An inclusion of integrated environmental assessments in this early phase is argued to stimulate consideration of environmental impacts from the start, and to make policy makers more prone to consider less conventional options during subsequent phases of the policy cycle as they have become more involved in the environmental impacts of chosen policy measures (Sheate et al., 2003).

- **Ex-ante assessment of policies measures:**
  In the decision phase, a policy measure is selected by policy makers based on its advantages and disadvantages (Vedung, 1997; Engels, 2005). The selection of the most appropriate policy measure is often based on a scientific assessment of the estimated costs, effectiveness and potential (environmental) side effects of the different potential policy measures (Engels, 2005). Cost-benefit analyses are often used to weigh the estimated cost of the different policy measures against their effectiveness, while integrated environmental assessments are commonly used to determine if the policy measures have any significant negative environmental impacts. All these assessments are referred to as ex-ante assessments because they take place before the policy decision (Vedung, 1997; Engels, 2005; Lee, 2006; Thiel, 2009).
Ex-post assessment of policy measures:
Ex-post assessment of policy takes place after policy measures have been taken and implemented, and are thus used to evaluate the policy measures (Vedung, 1997; Engels, 2005). The aim of these assessments is to check whether the chosen policy measures were indeed the best choice, and whether alternative policy measures would have performed better. Integrated environmental assessments provide a possible approach to perform such retrospective evaluations of applied policy measures (Engels, 2005; Lee, 2006; Sheate et al., 2003).

Monitoring of implementation:
Monitoring is also used to evaluate the chosen policy measures (Engels, 2005). A key difference with ex-post assessments of policy is that monitoring merely determines whether set targets have been achieved. Monitoring is typically performed in a routinely, standardized procedure by government officials (Engels, 2005). Integrated environmental assessments do not typically play an important role in this phase of the policy cycle.

1.3 The role of simulation models in integrated environmental assessments

Models play an essential role in integrated environmental assessments, as the complex nature of environmental systems hinders real-life experiments and models provide a computational laboratory. However, different research questions require different modelling approaches and various modelling methodologies are available for integrated environmental assessments. Here we list a number of broad modelling methodologies that are used in regional to global scale integrated environmental assessments across different scales, and highlight their approach to include multi-scale interactions:

Nested models:
This approach uses a chain of nested models, in which there is a clear top-down hierarchy. Higher level (global) models produce outputs which are then used as boundary condition in lower level (local) models: i.e. global models constrain local models. This approach often involves the use of scenarios, in which broad, coherent storylines are developed about future development pathways (Rounsevell et al., 2006; Verburg et al., 2006; Verburg et al., 2008; Moss et al., 2010). The boundary conditions of the models lower in the modelling chain are based on these general scenario storylines and any assumptions
regarding (uncertain) input parameters are consistent with the scenarios. A well-known example of a nested model/scenario approach is the IPCC/SRES study, in which different global development pathways have been envisaged based on assumptions regarding the level of future globalization, economic growth, technological development, etc. (Moss et al., 2010; Vermaat et al., in press). Using a sequence of nested models, the impact of these general scenario storylines were then calculated by: (1) modelling future CO$_2$ concentrations with energy emission models, (2) modelling climate change with climate models based on the new CO$_2$ concentrations, and (3) using these results to model the impact of climate change on other sectors (Moss et al., 2010). Several other studies exist that have used this nested model/scenario approach (ATEAM: Rounsevell et al., 2006; EURURALIS: Verburg et al., 2006; Verburg et al., 2008; SIAT/SENSOR: Uthes et al., 2010). In all these studies, the models lower in the modelling chain are spatially explicit and are used to downscale the results of the higher, global models to the local scale. The spatial resolution of these studies is often coarse, but can sometimes be surprisingly high given their often large geographical coverage (i.e. 1 km$^2$ in EURURALIS and SIAT/SENSOR while covering EU27). These studies typically rely on official data (Eurostat, EEA, USGS, OECD, FAOSTAT, etc.) and do not necessarily require additional data collection. A clear disadvantage of the hierarchical structure of this nested model/scenario approach is that bottom-up analyses cannot be performed. Although the overall structure of the modelling chain in the above studies is typically hierarchically top-down and nested, some small sub-parts of these modelling chains can nonetheless diverge and include some feedbacks (e.g. feedback between the models GTAP and IMAGE in EURURALIS: Verburg et al., 2006).

• **Bottom-up approach with upscaling:**
A bottom-up approach tries to capture the main bottom-up processes in a (set of) model(s). Bottom-up processes are small, local processes that can add up to very large changes when they simultaneously occur over a whole range of locations: i.e. a particular change might appear relatively small and seemingly unimportant, but can still have an enormous impact if it occurs almost everywhere (Easterling 1997; Cash and Moser, 2010; Wilbanks, 2007). Thus, the combined/accumulated impact of the changes at all these locations can be very large (Easterling 1997; Cash and Moser, 2010; Wilbanks, 2007). A bottom-up approach tries to capture the cause-and-effects of these changes in a generic (mechanistic) model and then aggregates these results to a larger, regional scale by including spatially explicit datasets with location factors (Uthes et al., 2010). Well-known examples of this approach are the agent based models that attempt to simulate
land use change by modelling the decision of farmers and other stakeholders (Uthes et al., 2010; Valbuena et al., 2010). Although this approach is very well suited to address bottom-up processes and feedbacks, it does have some disadvantages: (1) because not all important processes are bottom-up, these are often considered exogenous to the model and “forced” upon the modelling framework, requiring additional assumptions (Easterling, 1997), (2) this approach requires high quality data with a high spatial resolution, which is often not available in official datasets and necessitates additional data collection, (3) the intensive computing time required by these models often prohibits an extensive geographical coverage and often limits the application to case-studies.

- **Coupled modelling platforms:**
  This approach is based on a set of interlinked models and therefore somewhat similar to the nested model approach, but with the main difference that these models are not hierarchically linked (Van Ittersum et al., 2008; Uthes et al., 2010). Instead of higher models constraining the lower models, the models are linked by incorporating the real-world linkages between the different system components as full processes in the modelling framework. These models may operate at the same scale or address different scales. In case global and local scale models are linked, the approach allows feedbacks between local and global scale processes and can simulate bottom-up processes making it suitable for bottom-up analyses (Van Ittersum et al., 2008; Uthes et al., 2010). A disadvantage of this approach is that representation of detailed processes for different system components and at different scales requires additional parameters, which might make the results more prone to error propagation and make data collection difficult. Another disadvantage is that individual models sometimes have been designed for use at a different scale, and coupling these models can then result in some form of ‘scale-mismatch’ between models. A spatially explicit model is often used to bridge between bottom-up and top-down processes. There are many examples of these modelling platforms, such as land use models that embed a crop growth model (Van Ittersum et al., 2008; Uthes et al., 2010; Schaldach et al., 2011). Other examples include linking an agro-economic model with a biogeochemistry model (Leip et al., 2008) or a global vegetation dynamics model to a climate model (Foley et al., 1996; Bonan et al., 2003; Kucharik et al., 2000).

- **Multi-scale scenarios:**
  Scenarios (as cognitive models) are frequently used in impact assessments as a systematic way to describe/set the boundary conditions in a chain of nested
models. Interestingly, scenario studies are also attempting to cover multiple scales by developing separate scenarios for two or more scales and then linking those (Biggs et al., 2007). Some studies have linked scenarios by designing global scenarios up-front and then applying them to a regional scale. This (top-down) approach is mostly followed when consistent and clearly coupled scenarios are needed (Biggs et al., 2007). Another approach is to design independent scenarios and link them afterwards by grouping scenarios based on their (dis)similarity in the driving forces, processes, impacts, etc. that they included (Biggs et al., 2007). Linking different scale scenarios can be very rewarding as it highlights cross-scale drivers, processes, pressures, responses, etc. and confronts different stakeholder groups with these (Biggs et al., 2007). However, there are also disadvantages to linking scenarios across different scale. For instance, stakeholders developing local scenarios might feel too constrained by the need to ‘fit’ into a global scenario and be alienated from the resulting output. Loosely linked scenarios can also have the disadvantage that scenarios have become ‘too loosely linked’ and are no longer consistent or comparable (Biggs et al., 2007). These scenarios can be easily coupled to modelling frameworks and applied in impact assessments through the Story-and-Simulation approach, where scenario storylines are designed by stakeholders, passed on to modellers, and the resulting model then given back to the stakeholders as a tool for further improvements of the general storyline and/or model quantification (Alcamo, 2008). This interactive cycle of improvement can be repeated until an acceptable scenario and model is produced.

1.4 Thesis objectives

The multi-scale drivers and impacts of environmental change processes require assessments that simultaneously analyse both scales in integrated environmental assessments: i.e. a methodology that models broad macro-scale processes without superfluous detail, but that is also credible at finer, local scale (Cash and Moser, 2000; Rothman et al., 2009). Despite some successes in coupling global and local scale in integrated environmental assessments, all currently available approaches have disadvantages and a standard methodology is lacking (Rothman et al., 2009). The main objective of this thesis is therefore to link local specificity to global macro processes in integrated environmental assessments. For this, various multi-scale methodologies will be applied in a number of integrated environmental assessments. Based on lessons learned during these applications, the following questions will be answered:
• How can multi-scale interactions best be represented during the model selection phase?
• How can multi-scale interactions be applied during the modelling phase and what are the constraints?

1.5 Thesis overview

As stated, the overarching theme of this thesis is finding ways to improve integrated environmental assessment methodologies by linking local specificity to global macro processes. Chapter two presents a classical example of a chain of nested models, which will be used to downscale global development trajectories and EU policies on land use in different European river basins at a 1 km² resolution. As this study will broadly address the consequences of future EU policy, it can be seen as supporting the problem definition phase of the policy cycle but also as an ex-ante assessment. Chapters three and four will explore the use of downscaling and constraining broad scenarios to a set of much more narrowly defined scenarios (which specifically address the characteristics of future cultivation of biofuel crops in Europe). These more narrowly defined scenarios are used to set the boundary conditions for a chain of nested models to which an extra model is added lowest in the chain, to determine the impact of biofuel crop cultivation on landscape and biodiversity. Thus, chapters three and four present an example of a multiscale (top-down) scenario combined with a chain of nested models and is an ex-ante assessment of a policy measure (i.e. EU’s biofuel directive). Chapter five presents less of a top-down approach than the latter studies. In this study, several process-based models (i.e. coupled modelling platforms) will be combined to simulate different hydrological and ecological processes. These combined models are then used to calculate the impact of climate change scenarios at the (local) scale of an average, imaginary Dutch polder. Because the imaginary peat polder is characterized using real data from a set of existing polders in the Netherlands, it is assumed to represent an ‘average’ Dutch peat polder and that its results are applicable beyond a single case study. As this study reviews current water management practices in the light of climate change and does not simply quantify the (dis)advantages of a narrow set of selected policy measures, it therefore caters to the scientific warning and problem definition phases of the policy cycle. Chapter six describes a bottom-up approach to upscale carbon emissions measured at the plot level to the landscape scale. This study does not mechanistically simulate local processes producing carbon emissions (which was described as typical for a bottom-up approach in the previous section), but instead uses an empirical approach in which an average car-
Bon emission is estimated for various vegetation types and these estimates are then linked to a GIS-map with vegetation types.

Thus, all described modelling methodologies commonly used in integrated environmental assessments will be applied in this thesis. The last chapter contains a synthesis in which conclusions regarding the usefulness of these methodologies for policy makers and the policy process will be drawn based on the experiences in this thesis. This synthesis will try to address the thesis objectives formulated in the previous section using the lessons-learned during this thesis’ studies, and determine whether integrated environmental assessment methodologies are available for analysing global change at multiple scales that adequately support policy making.
References


