The **RUBICODE** Project

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Identifying and assessing socio-economic and environmental drivers that affect ecosystems and their services

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SUMMARY

Change on earth is not a new phenomenon as it has been taking place for billions of years, but what is of new concern is the scale, magnitude and speed at which change has been occurring over the last sixty years. Human activity has led to an increase in the risk of crossing critical thresholds, which could result in abrupt changes to social and ecological systems. To prevent and reduce further environmental degradation, and reverse it where possible, it is important to understand how and why change is occurring. The identification of drivers of environmental change, which is embedded in the way humans live, encompasses detecting the rate of occurrence, the spatial and temporal scales and examining the changes in quantity and quality of ecosystems. This report reviews research on existing knowledge of the drivers of environmental change in order to highlight commonalities, strengths and limitations. A common framework for environmental change does not exist and so, this report outlines a new conceptual approach (a coupled DPSIR-SES framework) as a means of aiding the investigation of the complex dynamics of the spatial and temporal nature of drivers of change as well as the identification of the internal and external disruptions influencing a defined ecosystem service. Concepts of resilience, stability, durability and robustness are examined through a case study on the oak seed dispersal ecosystem service. Demography is listed as the most referenced and discussed indirect driver of environmental change, while the most commonly referenced direct drivers include land use and cover change, and climate variability and change. Natural, physical and biological phenomena, diseases and wars are the least discussed direct drivers. The majority of studies focus on one spatial scale exclusively. Outcomes of this report also include the need for researchers to define their terms to reduce confusion and facilitate the rapid exchange of comparable information.

CONTENTS

I. INTRODUCTION

There is no more "frontier," no more empty continents, no more infinite sources and sinks. There is just the "high frontier" of outer space, which, as far as we know, is more barren than any terrestrial desert and vastly more expensive to get to. The idea that biophysical limits to growth are near as well as real is not just the fabrication of "doomsayers". Herman E. Daly (1987)

Change on earth is not a new phenomenon as it has been taking place for billions of years. Humans and all other organisms have and continue to modify their environments. Yet, what is relatively a new concern is the scale, magnitude and speed at which change has been occurring from the end of World War II until today (McNeely, 1995). The impacts resulting from human activity are so significant that the fundamental flows of chemicals and energy, which sustain life, are also being modified (Kates et al., 1990). The literature is replete with reports on the degradation of ecosystems, species extinctions and the current state of the environment. Debates of whether the natural ecosystem can continue to sustain current lifestyles and whether the earth's biophysical limits are rapidly being approached are still high on the agenda for ecologists, social scientists, economists, decision-makers and the media. Human activity has led to an increase in the risk of crossing critical thresholds and triggering abrupt changes to society and ecosystems (Costanza et al., 2006).

An ecosystem is a complex community of organisms interacting with each other and their physical environment (Carpenter et al., 2005:27). Ecosystems perform fundamental life-supporting services on which human welfare is dependent. Alterations to ecosystems will directly or indirectly affect the human population. Costanza et al. (1997) state how the world economy would come to an abrupt stop if ecosystems and their services ceased to exist. Therefore, the immediate need to prevent and reduce further environmental degradation, and reverse it where possible, is apparent for the sustainability of humanity. The identification of change and response of both humans and nature needs to be considered to effectively design strategies for sustainability. This need has led to the emergence of 'sustainability science', which sets out to identify and understand the dynamics of social and ecological changes while meeting the needs of society and ensuring environmental protection (Turner et al., 2003).

The process of identifying change encompasses detecting the rate of occurrence and the spatial and temporal scales as well as examining the changes in quantity and quality of ecosystems. Small changes may have large-scale impacts and large changes may have small-scale impacts, which is also to be considered (Costanza et al., 1997). To get to the "root" of change, it is critical to identify the agents, or drivers, of these changes, which is embedded in the way humans live. The values and goals of human populations govern the way societies manage resources and their surrounding environments (McNeely et al., 1995). The early detection of drivers of global environmental change is clearly a more cost-efficient approach to managing change (McNeely et al., 1995). Effective actions must be evidence-based, and derived from accurate information and knowledge of the problem, and responses should be directed at the drivers influencing change (Blum, 2004).

Significant environmental change research has been taking place, yet gaps exist in the complete understanding of the interactions between social systems and ecological systems as well as a common approach amongst the scientific community. In efforts to contribute to the reduction of these gaps, this project sets out to research existing knowledge on the drivers of change in order to highlight commonalities, strengths and limitations. A common framework on environmental change does not exist, thus this project develops a new conceptual framework (a coupled DPSIR-SES approach) as a means to aiding the investigation of the complex dynamics of the spatial and temporal nature of drivers of change as well as the identification of the internal and external disruptions influencing a defined ecosystem service. Moreover, the DPSIR-SES framework, in its exploratory phase, aims to stimulate new perspectives and discussion.

Specifically, the objectives of this report are to:

1. Review existing knowledge on anthropogenic and natural drivers of global environmental change and relevant scenario developments;
2. Identify drivers of environmental change, their corresponding definitions and frameworks as well as the strengths and weakness of the relevant studies;
3. Categorize the identified drivers into a qualitative matrix to illustrate commonly referenced direct and indirect drivers as well as to identify patterns and scales;
4. Integrate the social-ecological systems (SES) with the DPSIR framework to qualitatively explore the dynamic processes of a defined system and a selection of drivers.

For the purpose of this report, the following definitions from the Millennium Ecosystem Assessment (MA) will be applied for drivers of environmental change:

- **Drivers** of environmental change are any natural or human-induced factors that directly or indirectly cause a change in an ecosystem (Nelson et al., 2005).
- **Direct drivers** are the physical, biological or chemical processes that tend to directly influence changes in ecosystem goods and services (Nelson et al., 2005).
- **Indirect drivers** are factors that operate more diffusely than direct drivers, often by altering one of the more direct drivers (Nelson et al., 2005).

II. LITERATURE REVIEW

II.1 Objectives

The main aim of the literature review was to critically analyse published scientific literature regarding anthropogenic and natural drivers of environmental change that may influence ecosystems and their services directly and indirectly. Relevant scenario developments were also examined due to their contributions to the understanding of drivers. The spatial scales of the articles include local, regional and global scales, while the temporal scale includes articles from the present to the past, without a specific cut off time period, and scenarios up to 100 years into the future. The literature review aims at identifying the strengths and limitations of existing studies, which specifically involve the:

- Identification and categorization of drivers;
- Identification of environmental change terms and definitions;
- Identification of environmental change conceptual frameworks.

II.2 Methods

The available published literature concerning anthropogenic and natural drivers of environmental change has been identified by various methods, such as reviewing online scientific journals and databases, searching library sources, scanning reference lists of other literature reviews, viewing websites, and hand-searching books. The literature has been reviewed and the main findings have been summarized in Table A in Appendix I. A list of drivers has been developed and categorized together with a narrative review. The key words and data sources are listed in Appendix II.

II.3 Terms and definitions

Throughout the literature review, a diverse use of terms and meanings to define drivers of environmental change have been applied (see Table 1: Terms and definitions). Definitions vary in detail and drivers can range from natural forces (e.g. volcanic eruptions) to anthropogenic activities (e.g. agriculture). In many instances, definitions are not presented in the articles identified in the literature review and it is assumed that the reader is familiar with the relevant terminology.

A *driver*, as defined by the Millennium Ecosystem Assessment (MA), is *"any natural or human-induced factor that directly or indirectly causes a change in an ecosystem"* (Nelson et al., 2005). *Direct drivers* are *"physical, biological or chemical processes that tend to directly influence changes in ecosystem goods and services"* (Alcamo et al., 2005; Nelson et al., 2005) and *indirect drivers* are "*factors that operate more diffusely than direct drivers, often by altering one of the more direct drivers*" (Alcamo et al., 2005; Nelson et al., 2005). Using the MA definitions as a reference point, the inconsistencies of the terminologies being used within this research field as well as the positive developments are discussed below.

II.3.1 *Inconsistencies of terminologies*

The inconsistent use of terminology, contributing to a lack of clarity, is most noticeable in the following usages: same terms with different definitions; different terms with similar definitions; lack of differentiation between direct and indirect drivers, or primary and secondary drivers; and terms interchanged within articles. These points are discussed in further detail below.

Table 1: Terms and definitions of drivers identified in the literature[1]

Equivalent terms for 'driver' derived by the Millennium Ecosystem Assessment (MA)	
Drivers	Drivers of ecosystem services are any natural or human-induced factors that directly or indirectly cause a change in an ecosystem (Nelson et al., 2005, Millennium Ecosystem Assessment).
Environmental drivers	Exogenous or endogenous variables that cause measurable changes in properties of a community or ecosystem (Klug and Cottingham, 2001).
Non-climatic drivers	Drivers which influence systems directly and indirectly through their effects on climate variables such as albedo. Socio-economic processes can affect multiple systems. These drivers operate independently or in association with one another (Lepers et al., 2004 cited by Rosenzweig et al., 2007).
Direct drivers	Physical, biological or chemical processes that tend to directly influence changes in ecosystem goods and services (Alcamo et al., 2005; Nelson et al., 2005, Millennium Ecosystem Assessment).
Pressures	The various anthropogenic environmental pressures resulting from different socio-economic activities of human society (Alter-net, 2005).
Pressures	Emission (Berge et al., 1997).
Pressures	Mental and physical expressions of driving forces (e.g. emission to air) (Blum, 2004).
Drivers	Commonly used to refer to the variables that lead to degrading land cover change (Bray et al., 2004).
Proximal drivers	No definition (Dirzo and Raven, 2003).

[1] All definitions are identified in the literature review. Authors that define one term (e.g. indirect drivers) do not always define other terms (e.g. direct drivers).

Pressures	Developments in release of substances (e.g. emissions), physical and biological agents, the use of resources and the use of land by human activities (Gabrielsen and Bosch, 2003, EEA).
Proximate (or direct) causes of land use/cover change	Physical actions on land cover and usually limited to a recurrent set of activities such as agriculture (or agricultural expansion), forestry (or wood extraction), and infrastructure construction (or the extension of built-up structure). Proximate causes generally operate at local levels and are considered 'direct drivers of ecosystem change' (Geist et al., 2006:42-44).
Proximate causes of tropical deforestation	(Near-final or final) Human activities that directly affect the environment and appear to operate at the local level (Geist and Lambin, 2001).
Pressures	Stresses that human activities place on the environment caused by the driving forces (GIWA-EEA, 2001).
Driving forces	Actions that change nature from its conditions independent of humankind (e.g. population, technological capacity, socio-cultural organization) (Kates et al., 1990:11).
Proximate (or direct) causes of land use/ cover change	Human activities or immediate actions that originate from intended land use and directly affect land cover. Generally operate at the local level (Lambin et al., 2003).
Direct causes/ mechanisms	Include habitat loss and fragmentation, invasion by introduced species, over-exploitation of living resources, pollution, global climate change and industrial agriculture and forestry (McNeely et al., 1995:733).
Proximate sources of land use/cover change	Human activities that directly alter land cover with further environmental consequences that may ultimately feed back to affect land use (Meyer and Turner, 1992).
Stressors (on ecosystems)	This refers to abiotic or biotic (e.g. introduction of an alien species) variables that exceeds their range of normal variation, and adversely affect individual physiology or population performance in a statistically significant way. Stressors can be natural and anthropogenic (Vinebrooke et al., 2004).
Proximate causes (of deforestation)	Altered land management systems (Walker et al., 2000).

Equivalent terms for 'indirect driver' derived by the Millennium Ecosystem Assessment (MA)	
Indirect drivers	Factors that operate more diffusely than direct drivers, often by altering one of the more direct drivers (Alcamo et al., 2005; Nelson et al., 2005, Millennium Ecosystem Assessment).
Driving forces	Human activities leading to emissions, resource use and land use creating pressure on nature and the environment (Alter-net, 2005).
Driving forces	Societal trends and developments of the main economic sectors (Berge et al., 1997).
Driving forces	The causes of a certain state of soil. These forces can be cultural, economic, social, technical and ecological (Blum, 2004).
Driving forces	Social, demographic and economic developments in societies and the corresponding changes in lifestyles, overall levels of consumption and production patterns (Gabrielsen and Bosch, 2003, EEA).
Underlying (root or indirect) causes of land use / cover change	Fundamental forces that underpin the more proximate circumstances. They operate more diffusely (i.e., from a distance), often altering one or more proximate causes, and are formed by a complex combination of social, political, economic, demographic, technological, cultural and biophysical variables that constitute structural (or systematic) conditions in human-environment relations. Underlying causes may originate at the regional or global level (Geist et al., 2006:42-44).

Underlying driving forces (or social processes)	Fundamental forces that underpin the more obvious or proximate causes of tropical deforestation. They may operate directly at the local level or indirectly at the national and global levels (Geist and Lambin, 2001).
Driving forces	The socio-economic and socio-cultural forces driving human activities, which increase or mitigate pressures on the environment (GIWA-EEA, 2001).
Behaviour	The underlying rationales, both conditions and choices, for the actions that give rise to driving and mitigating forces (e.g. socio-political and economic structure) (Kates et al., 1990:11).
Underlying (root or indirect) causes	Fundamental forces that underpin the more proximate causes of land cover change and operate more diffusely (Lambin et al., 2003).
Indirect causes/ mechanisms (of biodiversity loss)	The factors that have led to the expanding ecological niche of humans. Indirect mechanisms are arguably more significant than direct mechanisms (McNeely et al., 1995:733).
Underlying (social) driving forces	Human goals that shape the proximate sources (human activities) (Meyer and Turner, 1992).

The use of same terms with different definitions

Frequently, the term *drivers* is used as a short form for *driving forces* of the European Environmental Agency (EEA) (personal communication with Joachim Spangenberg, July 2006). However, *drivers* as defined by the MA has a different meaning than *driving forces* of the EEA, as seen in Table 1. The confusion that may arise when using *drivers* synonymously with *driving forces* is that *drivers*, as defined by MA, include natural and anthropogenic factors that cause a direct or indirect effect on an ecosystem whereas *driving forces* are only social, demographic and economic forces that exert pressures (e.g. emissions) on the environment. Another example of the use of same terms with different definitions is displayed with the definition of *driving forces* by the Global International Water Assessment (GIWA) and EEA (2001), and the EEA (Gabrielsen and Bosch, 2003). The definition of *driving forces* by GIWA and EEA (2001) indicates that socio-economic and socio-cultural forces can either *'increase or mitigate pressures on the environment"* while the definition of the EEA (Gabrielsen and Bosch, 2003) does not discuss mitigating pressures. The EEA definition states that changes in production and consumption patterns result in pressures on the environment (Gabrielsen and Bosch, 2003). Although it is not mentioned, the assumption is that these forces lead to an increase in pressures and therefore, pose a negative effect on the environment, as opposed to having the ability to mitigate pressures. The interesting point to note here is that both definitions, although different, are defined by the EEA.

The use of different terms with similar definitions

Examples of different terms used to describe *indirect drivers* (MA definition) include *driving forces* (Gabrielsen and Bosch, 2003), *underlying causes* (Geist et al., 2006), *demands* (Tilman et al., 2001), *threats* (Kennish, 2002), *indirect mechanisms* (McNeely et al., 1995) and *agents* (Houghton, 1994), as presented in Table 1. Although there may be some minor differences, or even in some instances missing definitions, the underlying concepts of these terms are similar. All terms seek to understand the reasons why humans change their environment. Thus, all *indirect drivers* influence *direct drivers*. Socio-economic factors are also a repetitive theme throughout the definitions, followed by demographic, political and technological factors. Specifically, the EEA term, *driving forces*, refers to *'social, demographic and economic developments in societies and the corresponding changes in lifestyles, overall levels of consumption and production patterns'* (Gabrielsen and Bosch, 2003), whereas the factors of the MA's *indirect drivers* refer to the same attributes (Alcamo et al., 2005). The same applies for the use of the term *direct driver* (MA definition), where terms such as *pressures* (Gabrielsen and Bosch, 2003), *proximate, or direct, causes* (Geist et al., 2006), *direct mechanisms* (McNeely et al., 1995) and *stressors* (Vinebrooke et al., 2004) are used to present similar notions.

Lack of differentiation between direct and indirect drivers

A further complication is the lack of differentiation between *direct* and *indirect drivers*, or primary and secondary drivers, which exists throughout the literature, predominantly in the studies not related to deforestation and land use (Houghton, 1994; Kennish, 2002; Lake and Bond, 2007; Mikkelson et al., 2007; Olson et al., 2004b; Tilman et al., 2001; Walker et al., 2000). This may pose a problem for readers in comprehending the objectives and outcomes from these studies as both *direct* and *indirect drivers* serve to answer one research question with two different, but interrelated, components. *"Why do we [humans] transform the environment in the way that we do?"* This question was posed by Turner II (1990) and is the fundamental question of global environmental change research. Turner II explained that the first part of this question, "Why do we transform the environment?", seeks to identify the human actions that cause direct changes to the environment (e.g. industrialization causing pollution) while the second part, "…in the way that we do?", focuses on the underlying reasons as to why humans behave a certain way. Hence, the cause of environmental change is addressed by identifying *indirect drivers,* and the effects on the environment due to *indirect drivers* are explained through identifying the *direct drivers*. Responses aimed at ameliorating environmental degradation should be directed at the *indirect drivers* as opposed to remedying the negative impacts (Blum, 2004); therefore, a distinction between *indirect* and *direct drivers* is mandatory.

The use of terms interchangeably in articles identified in literature review

Taking into consideration the above mentioned concerns, a reader may face difficulty in understanding the context of an article if, within that article, terms such as *proximate causes* and *biophysical drivers* are used interchangeably (Mikkelson et al., 2007) without clear definitions being first introduced.

II.3.2 *Contributions to the research community*

Although the above ambiguities exist in the literature with respect to terminologies and definitions of drivers of change, the formulation and usage of these definitions has contributed substantially to the global environmental change research community. The emerging paradigm of global environmental change research has been captured and applied to the majority of definitions. Environmental change research involves detecting change, researching why, and monitoring how it occurs across spatial, organizational and temporal scales (Parr et al., 2003). This leads to the ability to make predictions about plausible future changes in order to develop effective policies to manage change (Parr et al., 2003). Researching the why and how is aimed at identifying and understanding the interconnectedness of human and natural systems. Accordingly, the paired definitions, *indirect* and *direct drivers* (MA definition), "fit" into these research objectives of examining respectively why and how global environmental change is occurring. The same applies to *driving forces* and *pressures* (Gabrielsen and Bosch, 2003), *underlying causes* and *proximate causes* (Lambin et al., 2003), and *indirect mechanisms* and *direct mechanisms* (McNeely et al., 1995). These paired definitions all seek to identify the underlying reasons that shape human activities and developments, which in turn, directly affect ecosystems. These definitions correspond to the notion of sustainable development, which is defined as *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (Brundtland, 1987).

Sustainable development aims at transforming human behaviours and values as a means to reduce environmental degradation and improve the quality of life within generations as well as between generations. Therefore, the identification of drivers of change, especially *indirect drivers*, would contribute to discerning the characteristics that need to be targeted in order to achieve sustainable development.

Three dominant definitions

In addition to capturing and applying the majority of definitions, three dominant sets of definitions have developed over the last decade, and in some instances, are still evolving. The first set of definitions are the terms, *underlying,* or *indirect/root, causes* and *proximate,* or *direct, causes,* derived by the Land-Use/Cover Change (LUCC) project of the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP) formalized in 1995 (Lambin et al., 2006). These terms are widely used within the relevant research and by researchers across the globe, including Mexico (Bray et al., 2004), Indonesia (Verbist et al., 2005), and Africa (Olson et al., 2004a). This reveals that a uniform language is developing amongst land use and cover change researchers. Importantly, these definitions have been refined throughout the years, resulting in greater descriptiveness and clarity. This is evident when comparing the definitions provided by Meyer and Turner II in 1992 to Geist et al. in 2006. Meyer and Turner II (1992) define *proximate sources* of land use/land cover change as *"human activities that directly alter the physical environment"* and *underlying driving forces* as *"human goals that shape the proximate sources*", whereas the definitions by Geist et al. (2006) also include attributes of spatial scale, multiple factor causations, and consider the complexities of social, political, economic, demographic, technological, cultural and biophysical factors. (Reference Table 1 for definitions).

The second set of definitions are *driving forces* and *pressures* derived by the EEA and linked to the DPSIR framework (described in Section II.4.1) developed in 1995. These definitions have contributed significantly to structuring, identifying and gathering information on anthropogenic socio-economic driving forces and their resulting environmental pressures. Although these definitions have not been generally applied within the land use and cover change research domain, they have gained widespread use across multiple disciplines, such as air pollution (Berge et al., 1997), soil degradation (Blum, 2004; Blum et al., 2004) and coastal ecosystems (Bidone and Lacerda, 2004).

The third dominant set of definitions are the terms, *direct* and *indirect drivers,* developed by MA in 2005, and are rapidly gaining popularity. In the book, *Land-Use And Land-Cover Change*, reference is made to *"direct drivers of ecosystem change"* when defining *proximate causes* as a means to provide clarity between different terminologies (Geist et al., 2006:43). In addition, one of the principal authors in the *Global Biodiversity Assessment* report refers to the MA as *"the best source of information on this topic"* (personal communication with Jeff McNeely, July 2007). *Direct drivers* can be physical, biological or chemical processes that influence changes in ecosystems. *Indirect drivers* are divided into five categories: demographic, economic, socio-political, scientific and technological, and cultural and religious (Carpenter et al., 2005:1:32). The MA definitions include natural factors, which are not included in the LUCC project and DPSIR definitions.

In examining the rationale behind the diverse use of the terms and definitions of drivers of change, it becomes apparent the research that has taken place within the last fifteen years has been carried out by authors from various backgrounds in different geographical locations. The scope of these studies has occurred at different spatial scales, in different timeframes and with different aims and objectives. Nevertheless, it is important that researchers define the terms used in their studies in order to reduce confusion, to facilitate the exchange of comparable information, and to ensure outcomes are not rejected due to a limited understanding of research scope. This is not to suggest that only one common terminology be applied, but to stimulate discussion on the need for clarity in this research field. As discussed above, three dominant sets of definitions have been developed and, if adopted and applied by researchers, could contribute to reducing ambiguity and enhancing clarity provided the researchers indicate to which definition they are referring.

II.4 Conceptual frameworks

Conceptual frameworks provide a means to examine and conceptualize phenomena in an orderly fashion, ultimately revealing patterns, which then typically lead to models that are conceptual, qualitative or quantitative and theories (Rapoport as cited by Berkes and Folke, 1998). Global change research widely uses frameworks to help identify the relevant characteristics of a specified system and to deconstruct these characteristics into manageable components in an effort to gain a deeper understanding of their interactions. Frameworks provide the basis for communication within and across disciplines.

There is no single universally accepted way of formulating the linkages between human and natural systems. (Berkes and Folke, 1998:9)

Various models conceptualizing the links between human and natural systems have developed, and a universal approach does not exist. Four dominant conceptual models identified in more than one article in the literature review are briefly described below. Table 2 presents the aims, strengths and weaknesses of three of these frameworks.

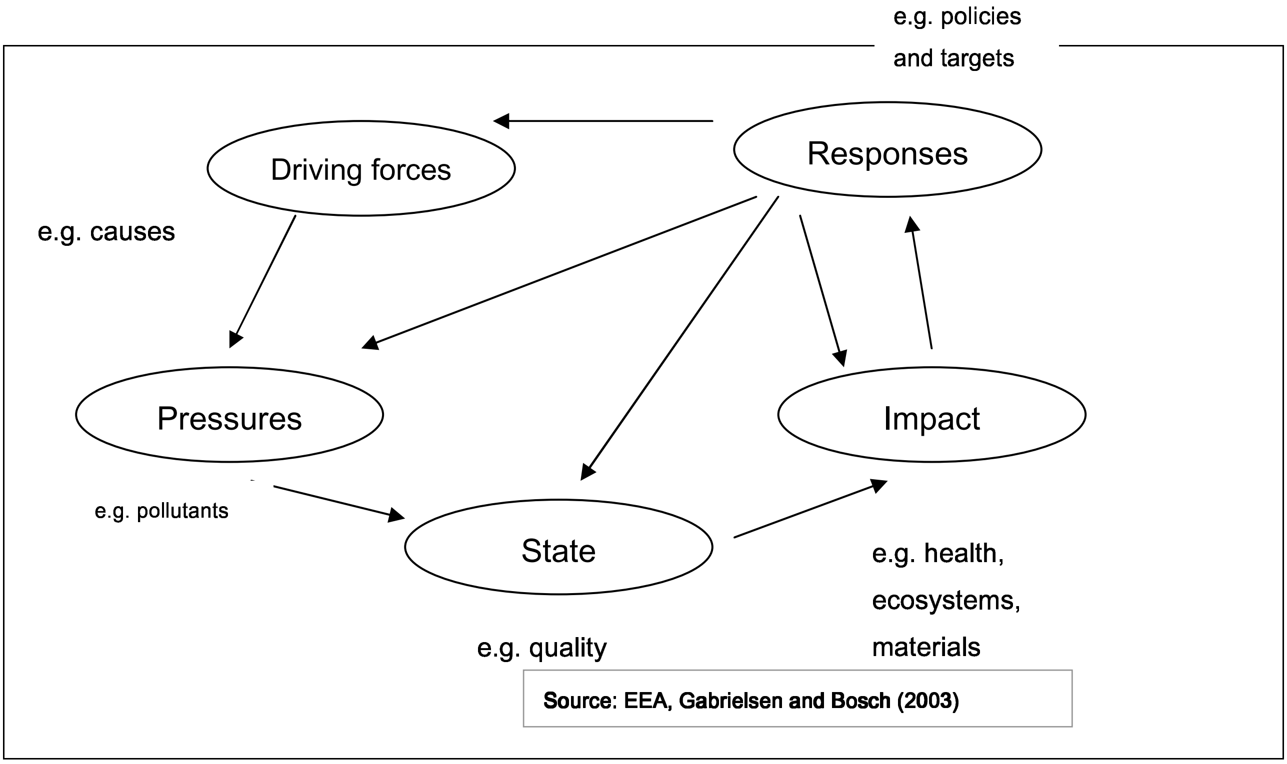
II.4.1 *DPSIR Framework*

The DPSIR is an analytical framework aimed at organizing, reporting and illustrating information on the effects of human activities on ecosystems. It was derived from the Stress-Response framework developed by Statistics Canada in the late 1970s and, as of 1995, has been widely used by the EEA and Eurostat (Gabrielsen and Bosch, 2003; Maxim and Spangenberg, 2006). In the literature review, 7 out of 45 articles applied this framework to their study or made reference to it (Alter-net R1, 2005; Berge et al., 1997; Bidone and Lacerda, 2004; Blum, 2004; Blum et al., 2004; Olson et al., 2004b; Vasconcelos et al., 2007). The framework is based on five elements (see Figure 1):

1. *Driving forces*, which are the social, demographic and economic developments that lead to the second point on this list;
2. *Pressures* on the environment, such as greenhouse gases or pollution;
3. *State* of the environment, which refers to the quantifiable and qualitative physical, biological and chemical conditions in a defined area, which then lead to the fourth point on this list;
4. *Impacts* on natural (e.g. biodiversity loss) and human systems;
5. *Responses,* which are the actions carried out by society and governments in efforts to minimize the negative impacts imposed on the environment, and feed back to the driving forces or pressures influencing anthropogenic developments.

Through its widespread use, the DPSIR framework has been the subject of critical examinations. It has been emphasized that this framework depicts only a linear and unidirectional causal chain with limited insight into the critical thresholds of each element (Barker, 2003; Maxim and Spangenberg, 2006; Olson et al., 2004b). However, the EEA point out that this framework can analyze dynamic complexities of various interacting forces through the five indicators (eco-efficiency, pathways and dispersion models, dose response, risk assessment costs and benefits of actions, and effectiveness of response) developed to act as links between the DPSIR elements (Gabrielsen and Bosch, 2003). Moreover, this framework contributes to conceptualizing problems in an understandable way and communicating them easily to various disciplines, including policy makers and stakeholders (Blum, 2004; Gabrielsen and Bosch, 2003; Maxim and Spangenberg, 2006). Its simplicity as a framework has been both complimented and criticized (Barker, 2003; Svarstad et al., 2007). The general agreement is not to reject the DPSIR, but to understand its limitations and further research them as a means to improving this approach (Svarstad et al., 2007).

Figure 1: DPSIR framework.



II.4.2 *IPAT Identity*

IPAT identity was introduced by Ehrlich, Holdren and Commoner in the early 1970s through debates on identifying the main anthropogenic driving forces of environmental change and understanding how these forces may influence the future (York et al., 2003). Ehlrich and Holdren state that environmental degradation is due to population growth, affluence and implemented technology (Gans and Jöst, 2005), and based on this concept, the mathematical identity IPAT was developed. IPAT is short for the equation:

I= P x A x T, where:

- I represents environmental impact;
- P represents population size;
- A represents affluence (normally measured by per capita consumption or production) and;
- T is the state of technology applied (e.g. impact per unit of consumption or production) (Gans and Jöst, 2005).

Thus, the multiplicative interrelationship between each variable is identified (York et al., 2003). IPAT has been widely used, mainly within ecological economics, due to its simplicity and clarity (Gans and Jöst, 2005; York et al., 2003). In 1992, Meyer and Turner II stated IPAT is *"[t]he single comprehensive approach to the question of driving forces"* (1992:51). However, since then, IPAT has been criticized due to conceptual problems as well as its limited ability to identify other driving forces, including policy and institutional factors (Gans and Jöst, 2005; Geist and Lambin, 2001; Kummer and Turner II, 1994). Furthermore, a neo-Malthusian view is embedded within this identity (Lambin et al., 2001).

II.4.3 *Political Ecology Framework*

The origin of 'political ecology' dates back to the 1970s when the term was coined by three commentators as a way to conceptualize linkages between nature and political economy (Peet and Watts, 2004). Blaikie and Brookfield (1987:17) state *"…the phrase 'political ecology' combines the concerns of ecology and a broadly defined political economy. Together they encompass the constantly shifting dialectic between society and land-based resources, and also within classes and groups within society itself"* (Olson et al., 2004b; Peet and Watts, 2004). Thus, the framework serves as an approach to better understand the interactions between social and physical factors that lead to land degradation. It involves the identification of social, economic, political and environmental drivers at multiple spatial scales and their interaction over temporal scales (Olson et al., 2004b). Furthermore, the 'land manager' is considered the leading factor influencing land use change within the scope of political ecology and nature-society studies (Blaikie and Brookfield (1987:239) cited by Peets and Watts, 2004). This ultimately implies that political and economic factors are the underpinning driving forces that in turn influence all other factors (e.g. social, environmental) (Peet and Watts, 2004). One of the limitations of this framework is the diversity of notions and meanings of ecology, politics and political economy (Peet and Watts, 2004).

II.4.4 *Socio-ecological systems*

Humanity is a major force in global change and shapes ecosystem dynamics from local environments to the biosphere as whole (Folke 2006). At the same time human societies and globally interconnected economies rely on ecosystem services and support as highlighted also by the Millennium Ecosystem Assessment. However, reality shows that our understanding of the nature of reality, science and management is incomplete (Norgaard, 2007) and that mainstream approaches to social and ecological sciences are disconnected and often reductionist. The history of the relationship between ecological and social sciences goes back to the 17th century when the separation of nature and society become a founding principle of Western academic organisations. Dualism between social and natural sciences, has been highlighted by several authors (Folke, 2003; 2006; Norgaard, 2007 etc). In most arguments it is generally accepted that natural and social systems are highly complex, but each is explained purely by internal disciplinary mechanisms. Social systems are seen as being isolated from the surrounding environment, where often the environment is only perceived as the source of resources and sinks. In natural systems, a large number of interconnections and variables is analysed, but the role of humans is often described by a single actor model where humans cause disturbance (Fischer –Kowalski, Weisz, 1999).

Many recent studies on ecosystem - social system interactions recognised that interactions exist between people, biodiversity and ecosystems. That is, changing human conditions drive, both directly and indirectly, changes in biodiversity, changes in ecosystems, and ultimately changes in the services ecosystems provide (MA, 2005). However to capture social and ecological dynamics the human dependence on the capacity of ecosystems to generate essential services, and the vast importance of ecological feedbacks for societal development suggest that social and ecological systems are not merely linked but rather interconnected (Galaz et al., 2006) or that the relationships between social and ecological systems are complex, based on mutual partnership and not domination over one other. To emphasize such a concept of humans-in-nature, Berkes and Folke (1998) use the term *social-ecological system (SES)*.

A major challenge is to find a way of matching the dynamics of ecosystems and social systems without reducing their independence relationship. The need to investigate whole SES arises from increasingly evidence that understanding and anticipating the behaviour of social and ecological parts of the SES requires account to be taken simultaneously of both components, meaning that SES are non-decomposable and emerge from the dynamic interplay between the social and ecological components (Gallopin, 2006). In other words the delineation between social and ecological systems is artificial and arbitrary (Folke, 2006). Thus, the special attribute of SES is that both subsystems are interlinked and therefore need to sustain each other in order to sustain the whole (Gatzweiler and Hagedorn, 2002). Illustrative examples of this are ecosystem services and their governance. The human dependence on the capacity of ecosystems to generate essential services is undeniable. Ecosystem services regulate and support natural and human systems through process such as cleansing, recycling and renewal of biological resources, and they are crucial for the sustainability of human development (Daily et al., 1997). To understand ecosystem dynamics we have to realize the importance of responding to ecosystem feedbacks for societal development and continuously learn about ecosystem processes to be able to design appropriate governance structures.

Gallopin (1991) defined SES as a system that includes societal (human) and ecological (biophysical) subsystems in mutual interactions[2]. Both social and ecological systems contain units that interact interdependently and each may contain interactive subsystems as well. Social systems includes economy, actors and institutions in mutual interaction. Institutions are understood here as *durable systems of established and embedded social rules* (convention, norms and legal rules) that structure social interaction (Hodgson, 2002) and thus are different from organisations and other actors. Institutions regulate the relationships among actors and between social and ecological systems (Ostrom et al., 1993, Gatzweiler et al., 2001). Ecological systems include self-regulating communities of organisms interacting with one another and with their environment (Folke, 2003). Using the concept of SES is especially important in the international research of global change, where understanding the dynamics necessarily involves the consideration of both the social and ecological components and their mutual interactions (Gallopin, 2006).

Dynamic management of SES systems must be an integrated and interdisciplinary process aiming at the interdependencies between institutions and ecosystems dynamics (Rammel et al., 2007; Gatzweiler, Hagedorn, 2002). Folke (2006) emphasizes that most studies of the social dimensions of resource and environmental management have focused on processes with social dimensions only and assume that if the social system is well organized institutionally it will also manage the available environmental resources in a sustainable way. A human society may show great ability to cope with change and adapt if analysed only through the social lens, but such adaptation may be at the expense of change in the capacity of ecosystems to sustain the adaptation. In fact, such adaptation can push ecosystems close to thresholds or into alternative states with a lower capacity to generate ecosystem services (Galaz et al., 2006). Similarly, focusing on the ecological side alone as a basis for decision making for sustainability leads to conclusions that are too narrow and flawed (Folke, 2006; Galaz et al., 2006). For example basing policy recommendations on ecological knowledge alone without recognizing the fundamental impact of social actors and institutions on

[2] Turner et al. (2003) called this system coupled human-environmental system.

ecological systems is a simplistic approach that fails to appreciate the complexity of governance processes (Adams et al., 2003) and the social features that enable management of dynamic ecosystems (Folke et al., 2005).

The issue of scale is also important in dealing with SES. Any SES refers to the subset of social and ecological subsystems nested in larger subsystems and in their interdependent relationships. For example, the mountain slope might be considered an ecosystem, but it is part of a larger mountain range that can also be considered to be an ecosystem. Similarly institutions, such governance or management can be considered hierarchically, as nested sets of systems from the local level (operational rules) to the regional (collective choice rules), national (constitutional rules) and international (Ostrom, 1990) levels. Likewise temporal scale is important, for example, where historical records about ecosystems and human society are interlinked across the present and future. The different scales or levels may be coupled through feedback relationships (Folke, 2003; Gunderson and Holling, 2002). Single scale analyses tend to reduce the number of interactions and outcomes and seriously affect SES dynamics. Matching dynamics between ecosystems and ongoing social-political processes such as governance is known as the problem of fit[3] (Galaz et al., 2006). The destructive result of social-ecological 'misfit' is evident in many resource management problems, which lack adequate coordinated responses from the social system, leading to constrained options for societal development and future capacity for adaptation (Gunderson and Holling, 2002; Berkes et al., 2003). To interpret and respond to ecosystem feedback the challenge lies not only in developing institutions for multi-scale ecosystem management, but also in examining the ways of enhancing adaptive capacity to deal with continuation changes, uncertainty and surprises and including external or internal drivers. Changes in ecological and social patterns and their inter-linkages are often unpredictable, especially due to the fact that the determinants of change are largely unknown and change over time (Gatzweiler, Hagedorn, 2002). The capacity to live with and learn from changes and unexpected shocks (the resilience), increases the likelihood of avoiding shifts to an undesirable stability domain and provide flexibility and opportunity for societal development and future capacity for adaptation (Folke, 2006; Galaz et al., 2006).

III. DISCUSSION

III.1 Categorization of drivers

The drivers of environmental change identified in the 45 articles in the literature review are categorized into a qualitative matrix to illustrate commonly referenced direct and indirect drivers as well as to identify patterns across themes and drivers. The matrix is divided into themes and drivers[4] (direct and indirect) derived from the Millennium Ecosystem Assessment (MA) report, *Ecosystems and Human Well-being: Scenarios, Volume 2* (Carpenter et al., 2005). The seven themes[5] include land, forests, biodiversity, freshwater ecosystems, coastal and marine ecosystems, atmosphere, and urban areas. The articles are not exclusive to one theme and some have been added to more than one category. Drivers are added to the matrix based on their relevant theme and the frequency of referencing as follows:

- *** Referenced in the majority of studies
- ** Referenced more than once but in less than half of the studies
- * Referenced in one study.

[3] The FIT is a function of the match between the characteristics of social norms (institutions) and the bio-geographical systems with which they interact (Young 2005).
[4] The five indirect drivers are from Chapter 1 (Carpenter et al., 2005) of the MA report and the twelve direct drivers are from Chapters 1, 7 (Nelson et al., 2005) and 9 (Alcamo et al., 2005).
[5] Definitions for each theme are in Appendix III: Definitions for themes

Table 2: Conceptual frameworks identified in the literature review

Framework	Aim	Strengths	Limitations
DPSIR – *analytical framework*	To organize, report and illustrate information on the interactions between human activities and ecosystems.	▪ The inclusion of the response element. ▪ Captures social drivers (Barker, 2003). ▪ Complex scientific problems can be conveyed in a format that policymakers can understand (Blum, 2004; Gabrielsen and Bosch, 2003; Maxim and Spangenberg, 2006). ▪ Applicable to a wide range of multi-disciplinary research. ▪ Simplicity and intuitiveness.	▪ A linear and unidirectional causal chain where interaction between variables within boxes are not considered (Barker, 2003; Maxim and Spangenberg, 2006; Olson et al., 2004b; UNEP-GEO, 2002). ▪ Spatial scale or temporal trends are not explicitly considered (Barker, 2003; Olson et al., 2004b). ▪ Causal relations assumed cannot express the complexity of the real world (Barker, 2003, Maxim and Spangenberg, 2006) ▪ Identification of critical factors/variables is difficult (Maxim and Spangenberg, 2006; Olson et al., 2004b). ▪ Framework is not based on socio-economic and ecological theories (Olson et al., 2004b). ▪ Environmental drivers of change not considered.
IPAT - *mathematical identity and accounting equation*	To analyze the impacts on the environment due to anthropogenic activities (York et al., 2003).	▪ Parsimonious analysis of the main driving forces of change (York et al., 2003). ▪ Identification of precise relationship between driving forces and impacts (York et al., 2003). ▪ Illustration of the correlations of driving forces and their impacts (York et al., 2003). ▪ Foundation in ecological principles (York et al., 2003).	▪ Incapable of hypothesis testing (York et al., 2003). ▪ Proportionality in the functional relationship between factors *a priori* is assumed (York et al., 2003). ▪ Non-monotonic and non-proportional impacts due to driving forces cannot easily be analyzed (York et al., 2003). ▪ Policy and institutional impacts are not considered (Geist and Lambin, 2001; Kummer and Turner II, 1994). ▪ The explanatory power of variables: population, affluence, and technology, is poor (Geist and Lambin, 2001). ▪ A neo-Malthusian view is evident as well as an exogenous role for technology in determining these limits (Lambin et al., 2001). ▪ At case study and regional levels, IPAT is insufficiently sensitive to capture the diversity, variability and complexity of real-world situations (Lambin et al., 2001).
Political Ecology Framework	To identify the causes of land use change that influence land degradation and biodiversity change (Olson et al., 2004b).	▪ Captures dynamics of interactions between political, economic and social processes at multiple geographic and temporal scales. ▪ Combines political and ecological dimensions.	▪ Diversification of notions and meanings of ecology, politics and political economy exist across (and within) disciplines, thus reducing coherency (Peet and Watts, 2004).

III.2 Indirect drivers

Table 3 presents the indirect drivers identified in the articles by theme (see Table 3.1 for corresponding references). The indirect drivers are divided into the five MA categories: demographic, economic, socio-political, scientific and technological, and cultural and religious.

Table 3: Indirect drivers identified in the literature review.

Theme / Indirect drivers	No. of studies	Demography	Economy	Socio-political	Science and Technology	Culture and religion
Land	16	***	***	***	**	**
Forests	7	***	***	***	*	*
Biodiversity	7	***	***	***	***	***
Freshwater ecosystems	1	***	***	***		
Coastal and marine ecosystems	4	***	**	**		
Atmosphere	4	***	***	*	**	
Urban areas	4	***	***	***	*	*

Table 3.1: Themes and corresponding references in relation to indirect drivers.

Theme	References
Land	Abildtrup et al., 2006; Alcamo et al., 2006; Blum., 2004; Blum et al., 2004; Busch, 2006; Dale, 1997; Houghton, 1994; Lambin et al., 2003; Meyer and Turner II, 1992; Nelson et al., 2001; Olson et al., 2004 a/b; Tilman et al., 2001; vanVuuren and Smeets, 2000; Verbist et al., 2005; Xie et al., 2005
Forests	Allen and Barnes, 1985; Bray et al., 2004; Geist and Lambin, 2001; Grainger, 1993; Kummer and Turner II, 1994; UNEP-GEO, 2002; Walker et al., 2000
Biodiversity	Alcamo et al., 2005; Alter-net RI, 2005; Kates et al., 1990; McNeely et al., 1995; Nelson et al., 2005; Spangenberg, 2007; UNEP-GEO, 2002
Freshwater ecosystems	Lake and Bond, 2007
Coastal and marine ecosystems	Bidone and Lacerda, 2004; Kennish, 2002; UNEP-GEO, 2002; Vasconcelos et al., 2007
Atmosphere	Berge et al., 1997; Nakicenovic et al., 2000; Rosenzweig et al., 2007; vanVuuren and Smeets, 2000
Urban areas	Alter-net RI, 2005; Redman, 1999; Seto and Kaufmann, 2003; UNEP-GEO, 2002

III.2.1 *Demographic indirect drivers*

Demographic indirect drivers are referenced in the majority of studies across all seven themes. The unquestionable view from the literature review is that the human population is one of the most important indirect drivers of global environmental change, since changes in population influence direct drivers such as resource and energy consumption, the amount of land required and the magnitude of pollution (Alcamo et al., 2005; Allen and Barnes, 1985; Kates et al., 1990; Ojima et al., 1994, Tilman et al., 2001).

In the land and forest studies, population fluctuations occurring over longer timescales significantly influence land use (Lambin et al., 2003), and migration is considered the most important demographic component influencing land use change at timescales of a few decades (Lake and Bond, 2007; Lambin et al., 2003; Verbist et al., 2005). These notions on demographic indirect drivers of land use and forest changes have developed within the last two decades as a result of extensive research. Prior to this, it was commonly thought that population growth in itself was the primary indirect driver of change. For instance, in 1985, Allen and Barnes supported that rapid population growth is the primary cause of deforestation. In rebuttal, Geist and Lambin (2001) present empirical evidence from 152 sub-national case studies on deforestation, stating that population dynamics are the fifth-most important indirect driver of tropical deforestation. Another example is displayed in the Philippines, where population growth occurred from 1970 to 1980 after deforestation took place and access roads were built for logging and non-logging purposes (Kummer and Turner II, 1994).

Population has various negative impacts on biodiversity. Human population density is directly connected to habitat loss (McNeely, 1995). This is evident in countries, such as Africa and China, where an average of 85% of their habitat has been lost due to extremely high population densities (McNeely, 1995). Population is linked to unsustainable consumption behaviour, and an increase in population assumes an increase in consumption, directly affecting natural resources (McNeely, 1995; UNEP-GEO, 2002). Furthermore, age distribution influences consumption patterns of a society (Alcamo et al., 2005). Population is also connected to increasing production of waste and pollutants, urban development, international conflict and inequities in wealth and resource distribution (UNEP-GEO, 2002). The biodiversity studies rarely discuss whether population is interrelated to other indirect drivers. Likewise, organizational, spatial and temporal scales are only briefly discussed. There is limited insight on these issues yet scale is the key concept that needs to be understood for the sustainability of biodiversity (Reid, 1995). In the UNEP-GEO report (2002), population is the fundamental indirect driver of biodiversity loss at the global level, but when biodiversity loss is discussed at regional levels, emphasis is attributed to the direct drivers of change as opposed to the indirect drivers.

In freshwater ecosystem studies, population is mentioned but not extensively discussed.

In coastal and marine ecosystem and atmospheric studies, population growth is significant because it causes urban growth, which is considered the main indirect driver of marine and coastal degradation (Kennish, 2002; Lambin et al., 2003; UNEP-GEO, 2002) and of air pollution (Nakicenovic et al., 2000). Specifically in atmospheric studies, rapid urban growth and shifts from rural to urban areas have influenced air quality across the globe. In Europe, an increase in air pollution occurred from 1960 to 1993, which is linked to a clear shift in population from rural areas to cities (Berge et al., 1997). Urbanization is expected to increase and thus, will continue to be a major indirect driver of air pollution (Nakicenovic et al., 2000). In addition, an aging population may be an indirect driver of air pollution (Nakicenovic et al., 2000). As the population ages, the number of people per household decreases and smaller households consume more energy per person than large households; however, this concept is in the preliminary research stage as uncertainties regarding the effects exist (Ironmonger et al., 1995 cited by Nakicenovic et al., 2000).

In urban studies, the main cause for urban growth at the global level is population increase (Redman, 1999; UNEP-GEO, 2002) and migration from rural to urban areas (UNEP-GEO, 2002). In Seto and Kaufmann's study (2003), population growth and migration were important indirect drivers of urban growth in the Pearl River Delta in China, but were not considered the main drivers of urbanization. Foreign investments and economic growth were the most important indirect drivers of urbanization in this region (Seto and Kaufmann, 2003).

There is widespread concern that excessive attention has been attributed to population growth and that population in itself often does not always have a significant effect on ecosystem changes (Geist and Lambin, 2001; Lambin et al., 2001; Meyer and Turner II, 1992). For instance, in 1995, water use declined in the United States by one-tenth from 1980, but the population increased by approximately 40 million people within that timeframe (McNeill, 2000) whereas Australia, with its small population, is one of the countries with the highest water consumption per capita (Lake and Bond, 2007). Furthermore, population, besides growth in numbers, is interlinked to other indirect drivers such as changing economic and labour markets, demands for products, and induced technological or policy changes, which have greater influences on ecosystems (Kaimowitz and Angelsen cited by Geist and Lambin, 2001; Lambin et al., 2001; Nakicenovic et al., 2000). In Lampung, Sumatra, during 1978 to 1988, the population doubled because of migration into the region due to the prospects of financial gains through coffee harvests (Verbist et al., 2005). This resulted in extensive deforestation. Another example involves the Spitzbergen and Greenland bowhead whale populations, which nearly became extinct because of Dutch and English sport whalers between 1610 and 1840 (McNeill, 2000). This is not to undermine demographic indirect drivers, but to highlight some of the generalizations being applied. One reason population may receive much attention is due to current ideologies. Popular ideologies on population growth include the Neo-Malthusian and Cornucopian view (Meyer and Turner II, 1992). The Neo-Malthusian view is that population growth must be controlled, if not reduced, as the world is full and additional population growth would result in irreversible environmental degradation (Meyer and Turner II, 1992). This view is embedded in the IPAT identity[6] (Lambin et al., 2001). In contrast, the Cornucopian view is that population growth stimulates technological and social advances, which results in bettering the quality of life (McNeely et al., 1995; Meyer and Turner II, 1992). Another reason that population is referenced so frequently may be due to the availability of demographic data.

III.2.2 ***Economic indirect drivers***

Economic factors are identified in the majority of studies within six of the themes (see Table 3). In coastal and marine ecosystems, it is referenced in more than one but in less than half of the studies.

In land studies, the global economy and international trade are two compelling economic forces that shape land uses at local and regional scales (Houghton, 1994; Lambin et al., 2003). Specifically, national debt and international trade are the main determinants of agricultural expansion (Houghton, 1994). In forest studies, economic factors (e.g. market growth, commercialization, urbanization and industrialization) are considered prevalent indirect drivers of deforestation, especially when operating in combination with other indirect drivers (Geist and Lambin, 2001; Grainger, 1993). For

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[6] Reference Section II.4.2 for description of IPAT identity

example, the international trade market demand for tropical woods was the core indirect driver of logging from 1970 to 1980 in the Philippines (Kummer and Turner II, 1994). Economic development can have both positive and negative impacts on deforestation as it can either speed up or control the process (Grainger, 1993). The distribution of wealth and income between developed and developing countries as well as between societies within countries is a significant economic indirect driver of tropical deforestation (Houghton, 1994) and biodiversity loss (Mikkelson et al., 2007). However, there is limited evidence about the connection of deforestation to local and national profits in per capita consumption (Kummer and Turner II, 1994) as well as about income distribution patterns within an economy (Mikkelson et al., 2007). In biodiversity studies, in addition to wealth and income distribution, ecosystem services are affected and modified due to economic development, which influences changes in the direct drivers of energy, resources and food consumption (Alcamo et al., 2005; Mikkelson et al., 2007). However, *"the relationship between income development and direct drivers differs greatly among ecosystem services"* (Alcamo et al., 2005). The overall size of the economy does not play such an important role on biodiversity loss as does the rate of conversion from inputs to outputs (Nelson et al., 2005).

Increasing industrialization and urbanization are the two main economic factors identified in freshwater ecosystem, coastal and marine ecosystem, and atmosphere studies responsible for influencing direct drivers including water pollution, habitat loss, shoreline developments and greenhouse gas emissions across all spatial scales (Bidone and Lacerda, 2004; Kennish, 2002; Lake and Bond, 2007; Nakicenovic et al., 2000). The speed at which urbanization occurs depends on the local economy and the characteristics of the landscape (Redman, 1999). For example, in the Pearl River Delta in China, agricultural land was converted to urban land between 1988 and 1996 due to rapid economic growth, foreign investment and decentralized policies (Seto and Kaufmann, 2003).

Tourism is identified in four studies as an economic indirect driver of environmental change (Blum et al., 2004; Kennish, 2002; Nelson et al., 2005; UNEP-GEO, 2002). Increasing growth in tourism has negatively contributed to soil and air pollution, coastal degradation and habitat loss (Berge et al., 1997; Blum et al., 2004; UNEP-GEO, 2002).

GDP (Gross Domestic Product) or GNP (Gross National Product) are widely used as socio-economic measures and are often the only indicators used (Abildtrup et al., 2006; Alcamo et al., 2005; Allen and Barnes, 1985; Tilman et al., 2001; Xie et al., 2005). Nevertheless, GDP and GNP do not consider all aspects of economic development (Bidone and Lacerda, 2004; Nakicenovic et al., 2000) and as a result, ecosystem services are not entirely accounted for in commercial markets (Costanza et al., 1997). Only one study uses a different economic index, namely the Human Development Index (HDI), which takes into account income, quality of life, health, and education of a given area (Bidone and Lacerda, 2004). The HDI is used in this study since the GDP fails to present the income and wealth distribution within the population, whereas the HDI results in showing that the level of income of the population is directly connected to the lack of sanitary conditions and is the indirect driver of pollution (Bidone and Lacerda, 2004).

A common view exists amongst several researchers that economic growth influences the indirect driver of technological progress, which in turn, contributes positively to the environment (Nelson et al., 2005). The Special Report on Emissions notes that pollution abatement efforts occur and clean technology is developed when there are increases in affluence (Nakicenovic et al., 2000).

III.2.3 *Socio-political indirect drivers*

Socio-political indirect drivers are referenced in the majority of studies linked to land, forests, biodiversity, freshwater ecosystems and urban areas (see Table 3). They are referenced more than once but in less than half of the coastal and marine studies, and only once in the atmosphere studies.

All themes highlight the critical role that policies have in transforming the earth. There is a common message identified across all themes, which is that poor or limited planning, the lack of policy enforcement, and the absence of policies have strong influences over the use and degradation of land, forests, biodiversity, water, air and urban development (Bidone and Lacerda, 2004; Geist and Lambin, 2001; Grainger, 1993; Kennish, 2002; Olson et al., 2004a; UNEP-GEO, 2002). For example, in the Amazonia, a core indirect driver of deforestation was the Brazilian government subsidies of cattle ranching (Grainger, 1993; Walker et al., 2000). Policies can also have positive and negative effects. An example of a positive policy impact on land use is seen in the case study in Santa Cruz, Mexico, where sustainability of the land occurred from 1984 to 2000 due to the existence of a secure land tenure regime (Bray et al., 2004) whereas a negative policy effect is visible in Southeast Asia where deforestation occurred due to weak governance (Kummer and Turner II, 1994). In forest studies, in addition to policies, political corruption is identified as an indirect driver of deforestation, usually due to unsustainable timber logging (Geist and Lambin, 2001). For instance, Kummer and Turner II (1994) discovered that political corruption was an indirect driver of deforestation in the Philippines from 1970 to 1980.

Furthermore, government policies can influence the rate and growth of population, migration and economic developments such as the price of energy, property rights and global regulations (Blum, 2004; Grainger, 1993; Lambin et al., 2003).

III.2.4 *Scientific and technological indirect drivers*

Science and technology are identified in the majority of biodiversity studies, more than once but in less than half of the studies in land and atmosphere, and only once in forest and urban area studies (see Table 3). In the freshwater, coastal and marine ecosystem literature, science and technology are not mentioned.

The general consensus is that technology can enhance environmental degradation (e.g. deforestation) and cause drastic changes but can also alleviate pressures and contribute to reducing pollution (Lambin et al., 2003; Rosenzweig et al., 2007). Decision-makers can strongly influence the accumulation of scientific and technical knowledge through setting priorities and by providing financial support (Nelson et al., 2005). Technology can influence the conversion rate of land (e.g. agricultural land converted to urban land) and the productivity of land (Seto and Kaufmann, 2003). In forest studies, technological factors are ranked as the third most important indirect driver of deforestation (Geist and Lambin, 2001). From the meta-analysis study of Geist and Lambin (2001), 46% of all case studies (152) are linked to agro-technological change (e.g. land use intensification), 45% are linked to applications in the wood sector (e.g. use of chainsaws or heavy equipment), and 18% are linked to agricultural production factors (e.g. land, labour, and capital).

Even though science and technology is listed as an indirect driver of environmental change in several studies, it is not discussed in detail and limited insight is provided on this topic.

III.2.5 *Cultural and religious indirect drivers*

Cultural indirect drivers are referenced in the majority of the biodiversity literature, in more than one but less than half of the land and atmospheric studies and in only one study of the forest and urban area themes (see Table 3). Cultural and religious indirect drivers are not referenced in freshwater, coastal and marine ecosystem studies. Religion is almost never mentioned and the focus is predominantly on cultural drivers.

In general, little attention has been attributed to cultural and religious indirect drivers in comparison with demographic, economic and socio-political drivers throughout the literature. Overmars and Verburg (2005) highlight that there is a lack of information about human processes and behaviours, specifically in land use and land cover change studies. The limited information on culture and religion may be due to the complexity of researching changing values, beliefs and norms, and their interconnections to anthropogenic transformations of the earth (Nelson et al., 2005). Cultural factors are linked to political and economic inequalities and are the foundation of decision-making (Lambin et al., 2003). In addition, when cultures have deteriorated, *"their social controls on land use are also degraded"* (Grainger, 1993:96).

Biodiversity studies note that humans alter the environment in order to satisfy their needs and desires (Kates et al., 1990). Therefore, human consumption behaviour and human perceptions of nature are significant indirect drivers of environmental change (Nelson et al., 2005). Consumption behaviours have not been extensively researched to date (Stern et al., 1997 as cited by Nelson et al., 2005). It is assumed that cultural and religious indirect drivers influence the trends of direct drivers of biodiversity (e.g. energy consumption, food consumption) (Alcamo et al., 2005).

III.3 Direct drivers

Table 4 presents the direct drivers referenced in the articles by theme (see Table 4.1 for corresponding references). Direct drivers are processes that cause direct changes to the environment. This section examines which direct drivers and their relevant components are most commonly addressed. The underlying purpose is to understand where attention has been attributed and why.

Within the seven themes, two out of the twelve direct drivers are most frequently referenced, namely land use and cover change, and climate variability and change. The first nine drivers listed in Table 4 have been identified more regularly than the last three: natural, physical and biological drivers; diseases; and wars. This may be due to various reasons. Diseases, wars and some elements of natural and biophysical components, such as earthquakes and volcanoes, often invoke abrupt and rapid changes to a given region and occur at transient intervals. Additionally, these drivers can be exogenous to the given ecosystem or region, thus making it complex to predict their occurrence and to understand the recovery time and resilience of the affected ecosystem. Another reason may be the difficulty of measuring these drivers, especially in the case of war.

Table 4: Direct drivers identified in the literature review.

	Land	Forests	Biodiversity	Freshwater ecosystems	Coastal and marine ecosystems	Atmosphere	Urban areas
No. of studies/	13	8	9	5	4	4	2
Direct drivers							
Land use/cover change	***	***	***	**	***	***	*
Habitat change			**		*		
Harvest and resource consumption	**	***	***				*
Over exploitation		**	**		*	**	
Climate variability and change (e.g. sea level rise)	**	**	***	***	*	*	
Air pollution	*		***	*		***	*
External inputs (e.g. irrigation, fertilizers, pest control)	*		**	***	***		
Energy use	*	**	*	*		*	*
Species introduction/ removal			***	*	*	*	
Natural, physical, biological (e.g. volcanoes, evolution)	*	*					
Diseases		*	*				
War		*	*				

Table 4.1: Themes and corresponding references in relation to direct drivers.

Theme	References
Land	Abildtrup et al., 2006; Alcamo et al., 2006; Blum et al., 2004; Busch, 2006; Houghton, 1994; Lambin et al., 2003; Meyer and Turner II, 1992; Nelson et al., 2001; Olson et al., 2004 a/b; Tilman et al., 2001; vanVuuren and Smeets, 2000; Verbist et al., 2005; Xie et al., 2005
Forests	Allen and Barnes, 1985; Bray et al., 2004; Geist and Lambin, 2001; Grainger, 1993; Houghton, 1994; Kummer and Turner II, 1994; UNEP-GEO, 2002; Walker et al., 2000
Biodiversity	Alcamo et al., 2005; Alter-net RI, 2005; Dirzo and Raven, 2003; McNeely et al., 1995; Mikkelson et al., 2007; Nelson et al., 2005; Sala et al., 2000; Spangenberg, 2007; UNEP-GEO, 2002
Freshwater ecosystems	Allan, 2004; Evans et al., 2005; Klug and Cottingham, 2001; Lake and Bond, 2007; Vinebrooke et al., 2004
Coastal and marine ecosystems	Bidone and Lacerda, 2004; Kennish, 2002; UNEP-GEO, 2002; Vasconcelos et al., 2007
Atmosphere	Berge et al., 1997; Dale, 1997; Nakicenovic et al., 2000; Rosenzweig et al., 2007
Urban areas	Seto and Kaufmann, 2003; UNEP-GEO, 2002

To understand the impact and magnitude of these direct drivers on a given ecosystem, knowledge of the baseline conditions of that ecosystem is imperative prior to the interaction of these drivers. War is a controversial issue and to gather information is challenging. Diseases in general may not be important enough as direct drivers of environmental change, since infectious wildlife diseases are only considered significant when they threaten human health or agriculture (Daszak et al., 2000). The reasons as to why the focus of the scientific community has been attributed to chronic and relatively more predictable direct drivers (e.g. land use change), which are predominantly endogenous to the defined systems as opposed to the transient disruptions (e.g. war), with the exception of climate variability, are not clearly understood. All direct drivers are discussed below in the order presented in Table 4.

III.3.1 *Land use and cover change*

Land use and cover change are identified in all themes. It is referenced in the majority of studies of land, forests, biodiversity, coastal and marine ecosystems, and atmosphere. It is referenced more than once but in less than half of the studies of freshwater ecosystems, and in one study of urban areas.

Of the 14 land studies, 7 specifically focus on agricultural expansion as the type of land cover change (Abildtrup et al., 2006; Busch, 2006; Dale, 1997; Olson et al., 2004a; Tilman et al., 2001; van Vuuren and Smeets, 2000; Verbist et al., 2005). The other articles address issues such as agricultural reduction (Xie et al., 2005), land and soil degradation (Blum, 2004; Blum et al., 2004), land use and property rights (Nelson et al., 2001), population growth and land use (Meyer and Turner II, 1994), and all types of land cover change (Alcamo et al., 2006; Lambin et al., 2003). Agricultural expansion is identified as a direct driver in all the 8 forest studies, followed by other land cover and use changes (e.g. logging, wood extraction, infrastructure development).

Land use and cover change are considered the most severe direct driver of biodiversity loss, specifically at the global level (Alcamo et al., 2005; McNeely et al., 1995; Sala et al., 2000). Various land changes are identified in the biodiversity literature but agricultural activities and deforestation are most commonly noted (Dirzo and Raven, 2003; McNeely et al., 1995; Nelson et al., 2005; Spangenberg, 2007). Land use and cover change are expected to continue to be a significant direct driver of ecosystems in the near future (Alcamo et al., 2005).

In studies of freshwater, coastal and marine ecosystems, the emphasis is on hydrological changes, water diversion and dams as well as agricultural, urban and industrial expansions (Evans et al., 2005; Kennish, 2002; Lake and Bond, 2007; Vasconcelos et al., 2007). Shoreline developments and dredging are important direct drivers in relation to coastal and marine ecosystems (Kennish, 2002; Vasconcelos et al., 2007).

Changes in land use significantly impact climate by influencing albedo and evaporation, changing air quality and pollution that affects the greenhouse process, and magnifying the effects of extreme climatic events (Dale et al., 1997; Rosenzweig et al., 2007). In urban area studies, one article presents land cover change from agricultural to urban land (Seto and Kaufmann, 2003).

The construction of roads has been identified as both a direct and indirect driver of environmental change. It is considered an indirect driver of deforestation because roads provide access for large numbers of people to migrate into new areas (e.g. the agricultural population in search of new lands) (Allen and Barnes, 1985; Bray et al., 2004; Geist and Lambin, 2001; Grainger, 1993). Roads have been noted as one of the main indirect drivers of deforestation in East Kalimantan, Indonesia, the Brazilian Amazonia, and other areas in Latin America (Geist and Lambin, 2001; Grainger, 1993). Additionally, the fast growth in transport, both air and road, has contributed to air pollution problems across the globe, specifically in the EU (Berge et al., 1997). However, road construction also has a direct impact on land since, in order to build roads, the existing land cover is cleared. In a study by Geist and Lambin (2001), road construction is considered as a proximate cause (i.e., direct driver) of deforestation.

III.3.2 *Habitat change*

Habitat change occurs either naturally (e.g. earthquakes, volcanoes) or through human-induced activities (e.g. agricultural expansion, urban expansion, construction of roads), which are in fact the more common cause for change.[7] Habitat change and fragmentation are identified in only two themes: biodiversity, and coastal and marine ecosystems. Habitat changes cause significant biodiversity loss as the balance between species and their ecosystems is disrupted (McNeely et al., 1995; Spangenberg, 2007).

Habitat change, and land use and cover change appear to have similar meanings and to measure similar characteristics. The definition of land cover includes habitats (reference definition by Lambin et al., 2006 in Section III.3.1). Land use and cover changes are the transformations of the physical environment, which again include changes to habitats. Anthropogenic activities, such as agricultural expansion and urban development, change land cover, which generally result in changes in habitats if not considered during planning phases. Land use and cover changes have severe impacts on biodiversity loss, which are part of habitats. Thus, habitat change is already considered in land use and cover change. The different terms may have developed as a result of different classifications and perspectives from ecologists and social scientists respectively.

III.3.3 *Harvest and resource consumption*

Harvest and resource consumption are identified as direct drivers in themes of land, forests, biodiversity and urban areas (see Table 4). In themes of forest and biodiversity, harvest and resource consumption are referenced in the majority of studies. In land studies, they are referenced more than once but in less than half, and in urban area studies, they are referenced only once. Within the land, forest and biodiversity literature, wood extractions (Allen and Barnes, 1985; Dirzo and Raven, 2003; Geist and Lambin, 2001; Kummer and Turner II, 1994; van Vuuren and Smeets, 2000; Verbist et al., 2005), mining (Alcamo et al., 2005; Alter-net R1, 2005; Dirzo and Raven, 2003; Grainger, 1993), fishing (Dirzo and Raven, 2003) and harvesting of species (Alter-net R1, 2005; Dirzo and Raven, 2003) are commonly listed as the processes which directly influence environmental change. In urban area studies, resource consumption is the cause of environmental urban degradation (UNEP-GEO, 2002).

The point at which resource and harvest consumption pass a critical threshold where they are no longer considered sustainable, and are thus categorized as over-exploited, is not clearly defined. For instance, Allen and Barnes (1985) state that regulated timber extractions should not cause permanent damage to forests (cited from Schmithiisen 1976) but that only uncontrolled timber extractions cause serious damage. A common tree canopy threshold to define forests does not exist, contributing to the complexity of measuring and determining what constitutes “serious damage”. The MA uses a canopy cover of at least 40% whereas the Food and Agricultural Organization

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[7] http://www.greenfacts.org/glossary/ghi/habitat-change.htm Visited on September 7, 2007.

(FAO) uses a 10% tree canopy threshold. Still different is the IGBP, which uses a 60% threshold (Scepan, 1999 as cited by Nelson et al., 2005).

III.3.4 *Overexploitation*

Overexploitation is identified in more than one but in less than half of the forest and biodiversity studies, and in one study of themes of land, coastal and marine ecosystems, and atmosphere (see Table 4). Specifically, exploitation of resources (Dirzo and Raven, 2003; Kennish, 2002; McNeely et al., 1995; Rosenzweig et al., 2007; Spangenberg, 2007), over-harvesting of resources (UNEP-GEO, 2002) and over-grazing of resources (Dale, 1997; UNEP-GEO, 2002) are listed as direct drivers. In addition, uncontrolled timber extractions and uncontrolled grazing (Allen and Barnes, 1985) as well as the illegal harvesting of resources (e.g. narcotics) (Grainger, 1993) influence biodiversity.

III.3.5 *Climate variability and change*

Climate variability and change refers to temperature and precipitation and their variability and extremes as well as sea level rise in relation to marine systems (Nelson et al., 2005). Climate is identified as a direct driver in all themes except urban areas (see Table 4). Specifically, climate is referenced in the majority of the biodiversity and freshwater ecosystem studies, in more than one but in less than half of the land and forest studies, and once in coastal and marine ecosystem and atmosphere studies.

The global average surface air temperature has increased since the 1860s, yet the spatial and temporal scales vary (Nelson et al., 2005). Land transformations influence climate changes (Lambin et al., 2003) and have been linked to changes in air quality and pollution (Rosenzweig et al., 2007). Forests are naturally affected by climate and extreme climatic events (Allen and Barnes, 1985; UNEP-GEO, 2002). Climatic factors such as forest fires (Blum et al., 2004), drought events (Vinebrooke et al., 2004), and sea level rises (Kennish, 2002), are identified within the literature; however, excluding atmospheric studies, climate is not discussed in detail beyond observed changes.

III.3.6 *Air pollution*

Air pollution is referenced in the majority of biodiversity and atmospheric studies. It is referenced once in land, freshwater ecosystem, and urban area studies (see Table 4). It is not identified in themes of forests and coastal and marine ecosystems. Specifically, greenhouse gases (Alcamo et al., 2005; Dale, 1997; Nakicenovic et al., 2000), acidification (Alcamo et al., 2005; Sala et al., 2000; Spangenberg, 2007) and CO_2 enrichment, considered the most important greenhouse gas, (Alcamo et al., 2005; Dale, 1997; Evans et al., 2005) are highlighted. The main sources of air pollution include the burning of fossil fuels, agricultural activities, industrial processes and deforestation (Alcamo et al., 2005).

III.3.7 *External inputs*

Irrigation, fertilizers, nutrients, and pest control chemicals are external inputs in accordance to MA. External inputs are identified in four themes (see Table 4). They are referenced in the majority of studies of freshwater, coastal and marine ecosystems, in more than one but in less than half of the biodiversity studies, and in one land study. In the freshwater, coastal and marine ecosystem studies, nutrient enrichment, and organic and inorganic contaminants at all spatial scales are identified in all

5 of the freshwater studies and in 3 of the coastal and marine ecosystem studies (Bidone and Lacerda, 2004; Kennish, 2002; Vasconcelos et al., 2007). Irrigation, and nitrogen and phosphorus fertilizers are noted as direct drivers of land use and cover change (Lambin et al., 2003).

III.3.8 *Energy use*

Energy use as a direct driver of environmental change is identified once in land, biodiversity, freshwater ecosystem, atmosphere and urban area studies. It is referenced more than once but in less than half of the forest studies. It is not identified in the marine and coastal ecosystem literature. The extraction and mining of coal, fossil fuels, iron, oil, gas and petrochemicals directly influence changes in ecosystem goods and services (Geist and Lambin, 2001). Wood extractions are also used for the purpose of fuel wood, along with the various other purposes (e.g. furniture, construction, housing). Energy production is the primary direct driver of greenhouse gases (Alcamo et al., 2005). Energy consumption is influenced by the indirect drivers of the demand for energy, which is linked to population growth and the economy, the affluence of a society or nation, and energy technologies (Alcamo et al., 2005; Geist and Lambin, 2001).

III.3.9 *Species introduction and removal*

Humans are re-organizing ecosystems through the intentional and unintentional introduction and extinction of species across the globe, causing massive alterations to species ranges (Nelson et al., 2005). Species invasions are recognized as a global phenomenon, impacting most regions (Mack et al., 2000 cited by Nelson et al., 2005), but a definition has not been unanimously agreed upon within the scientific community (Nelson et al., 2005). Species introduction and removal are noted as a direct driver in four themes (see Table 4). It is referenced in the majority of biodiversity studies and is a direct cause of biodiversity loss (Dirzo and Raven, 2003). However, the introduction of species into a new ecosystem may have both positive and negative impacts (McNeely et al., 1995). Negative impacts include the degradation of the health of humans and other species as well as the introduction of diseases (Vitousek et al., 1997). Economic damages can also result from species introduction, such as in the invasion of zebra mussels in North America, resulting in billions of dollars in losses (Vitousek et al., 1997). Importantly, biological invasions are rooted in social, economic and political indirect drivers (Dirzo and Raven, 2003). The uncontrolled introduction of genetically modified organisms is noted in one paper (Spangenberg, 2007). Species introduction and removal are referenced once in the themes on freshwater ecosystems, coastal and marine ecosystems, and atmosphere. The removal of fish is also of high concern in coastal and marine ecosystems (Vasconcelos et al., 2007).

III.3.10 *Natural, physical and biological drivers*

Natural, physical and biological drivers are identified in two articles, one being in the land study (Verbist et al., 2005) and the other being in the forest study (Geist and Lambin, 2001). The characteristics of the biophysical environment (e.g. soil quality, topography, altitude) are discussed in both studies, which in fact do not actually *drive* environmental change, but significantly contribute to shaping land use decisions and changes (Geist and Lambin, 2001). For instance, one of the contributing factors to the development of coffee gardens in Sumberjaya, Lampung, was the soil suitability, the ample and regular rainfall, and the appropriate altitude (Verbist et al., 2005).

III.3.11 *Diseases*

Diseases are identified as a direct driver of environmental change in one study on biodiversity (Nelson et al., 2005). Biological invasions and the introduction of pathogens into different ecosystems can impact both the health of humans and species (Nelson et al., 2005).

III.3.12 *War*

War is identified in only two articles (see Table 4). One is identified in the forest theme and the other in biodiversity. In the forest study, social trigger events, which include war, act as direct drivers of deforestation and are important in Africa and China (Geist and Lambin, 2001). War is considered a direct and indirect driver of ecosystems (Nelson et al., 2005). It is a direct driver through factors such as the testing and usage of weaponry and bombs (e.g. nuclear, chemical, biological), the death of humans and animals, habitat fragmentation, and loss. An example is the destruction of the Vietnamese forests due to the airborne release of the pesticide chemical, Agent Orange (Nelson et al., 2005). The impact of military preparedness and militarism on the environment depends on factors such as the magnitude and type of war and weaponry. War acts as an indirect driver by influencing land use changes, possibly due to the destruction of infrastructure, forests, etc., or the establishment of military settlements, the manufacture of weaponry, the construction of new roads, the overexploitation of marginal resources, and in extreme situations, famine (Nelson et al., 2005). Also, war operates with other indirect drivers, such as demographic (e.g. migration), social (e.g. poverty) and economic (e.g. loss of income and labour). In 1997, as a result of armed conflicts, 23 million people left their countries in search of refuge elsewhere (Krug, 2002 as cited by Nelson et al., 2005).

III.4 Scale, level and speed

…..scale of the management problem has far surpassed the scale of the institutions that have been developed for local environmental management. Costanza et al. (2000)

Within the last fifty years, humans have altered their environments at a speed, magnitude and scale that have never existed before (McNeill, 2000; Vitousek et al., 1997). The issue of scale, level and speed is crucial to understanding environmental change. *"Scale is the spatial, temporal, quantitative or analytic dimensions used by scientists to measure and study objects and processes"* (Gibson et al., 2000). *"Levels (e.g. micro, meso and macro) are the units of analysis that are located at the same position on a scale"* that are generally ordered hierarchically (Gibson et al., 2000). Drivers interact across different spatial, temporal and organizational scales and at multiple levels within these scales (Lambin et al., 2003; Nelson et al., 2005). Drivers can operate slowly or rapidly, over long or short timeframes, in combination with other drivers and with feedback mechanisms between drivers (Lambin et al., 2003; Olson et al., 2004b).

More than half of the studies in the literature review make reference to scale, of which many specify the spatial and temporal scales being examined (see Appendix I). Although scale is noted in the literature, often the delineation of boundaries between the various scales (e.g. local to regional, regional to global) is not efficiently defined. Moreover, the interconnection between drivers within these dimensions (e.g. cultural values and their influences on economic indirect drivers) is not clearly addressed. More often than not, the timeframes and locations selected for the study are based on the availability of data.

The majority of studies across all themes, with the exception of atmosphere, focus on one scale exclusively. Specifically, the land studies address local scales (Nelson et al., 2001; Verbist et al., 2005; Xie et al., 2005), national scales (Olson et al., 2004b; van Vuuren and Smeets, 2000) and global scales (Meyer and Turner II, 1992; Tilman et al., 2000; UNEP-GEO, 2002). Also, a few land studies research multiple scales (Abildtrup et al., 2006; Alcamo et al., 2006; Blum, 2004). The forest studies focus predominately at the national or sub-national scale (Allens and Barnes, 1985, Geist and Lambin, 2001; Kummer and Turner II, 1994; Walker et al., 2000). This is because at this specific spatial scale, the dynamics of drivers of environmental change are thought to be better understood (Geist and Lambin, 2001). The majority of biodiversity studies address the global scale (Alter-net R1, 2005; Dirzo and Raven, 2003; Kates et al., 1990; McNeely et al., 1995; Sala et al., 2000; UNEP-GEO, 2002). Almost all of the freshwater, marine and coastal ecosystem studies focus at the local scale (Allan, 2004; Bidone and Lacerda, 2004; Evans et al., 2005; Klug and Cottingham, 2001; Vasconcelos et al., 2007) and one study is at the regional scale (Lake and Bond, 2007). Atmospheric studies examine multiple scales, specifically global and regional (Berge et al., 1997; Nakicenovic et al., 2000; Rosenzweig et al., 2007), and urban studies are at local scales (Redman,1999; Seto and Kaufmann, 2003).

The common method of examining spatial scales is to begin with the identification of global drivers, which are then downscaled to other spatial scales (e.g. regional or local) (Abildtrup et al., 2006; Alcamo et al., 2005). The process of downscaling, or up-scaling, drivers is complex, since drivers can be ‘scale-specific’, meaning that a driver at location A may act differently or even be less important at location B (McNeely et al., 1995; Olson et al., 2004b). An example is displayed in Mount Kenya where, at the broader level, it appears that the land is sub-divided into fenced farms; however, at the plot level, the image is different; the farmers have abandoned the fields and cultivation is not taking place due to the low productivity of the area (Olson et al., 2004b). Meyer and Turner II (1992) recommend a middle scale between global and local be created through which drivers can be addressed and better understood whereas Olson et al. (2004b) state a multi-scale approach is mandatory to fully understand drivers, their trends and impacts.

Globalization has been identified in three studies, two of which are on land (Lambin et al., 2003; Olson et al., 2004b) and one of which is on biodiversity (Nelson et al., 2005). In the land studies, globalization influences indirect drivers and it can either increase or decrease the impacts of these drivers on land use (Lambin et al., 2003). Even though it is often listed as a driver of environmental change (e.g. Nelson et al., 2005), it is a dynamic as well as homogenizing *process* that plays a critical role in shaping environmental change drivers. It operates on many spatial and temporal scales, which influences the speed of interactions, intensification and multiplication of linkages of drivers (Held et al., 1999 cited by Young et al., 2006). It contributes to the rapid increase in movement of goods, services, consumption, ideas and people as well as poverty, hunger, food insecurity, diseases and national debts (Hibbard et al., 2005). Importantly, globalization has been linked to the decline in diversity: biodiversity, institutional diversity, ethnic diversity, cultural diversity, technological diversity and diversity of values (Young et al., 2006).

III.5 Research limitations

Some of the key limitations identified in the literature review are highlighted in this section. The aim is to shed light on these obstacles as to encourage researchers to explore and overcome them in order to further enhance global environmental research.

III.5.1 *Scenarios*

Scenarios for biodiversity, urban areas, freshwater, and coastal and marine ecosystems are not comparable to those of climate change and greenhouse gases (Sala et al., 2000) and land studies. Therefore, only a select part of the "puzzle" is being examined in detail.

III.5.2 *Different classification systems*

The importance of common terminology and the complications that arise from using terms without definitions have been highlighted. Important to also consider is the different classifications that exist across the various disciplines (e.g. ecology, earth science) and institutions (e.g. MA, EEA, UNEP). An example is that ecologists divide the world into categories based on vegetation and not land use, as do agriculturists (Houghton, 1994). Another example is that the MA and FAO have different percentages for canopy cover thresholds to define forests, 40% and 10% respectively. These differences create difficulties when comparing information and when deciding upon what scale or level is important to examine.

III.5.3 *Adequate information of indirect drivers*

The level at which adequate explanation is achieved in order to define the dynamics of indirect drivers has not been reached amongst researchers (Meyer and Turner II, 1992). For instance, the explanation for deforestation due to agricultural expansion may be indirectly linked to population growth by some and indirectly linked to socio-political and economic indirect drivers, which also stimulates population growth, by others (Meyer and Turner II, 1992). Still others may discuss the role of agricultural expansion in influencing population growth (Meyer and Turner II, 1992). This complication may be due to the lack of clear definitions, the non-existent selection criteria for drivers and/or the lack of a common integrative framework.

III.5.4 *Population*

One of the main indirect drivers of environmental change is demography. Population influences resource consumption, food production, pollution, waste production and so forth, but population growth does not assume a proportional increase in resources, food, pollution, and waste, as this would imply an even distribution between population and these factors. Caution, therefore, should be taken when generalizing on the impacts of global population on the environment. Demography is interlinked to social, economic, ecological and political indirect drivers, which substantially affect population growth. Thus, it cannot be examined independently of these drivers. The excessive attention attributed to demography as a global indirect driver of environmental change may be linked to other reasons, such as political decisions, ideological values, and simply, the availability of data (as mentioned in Section III.2.1). Scenarios predicting the global future population are highly uncertain and a complex task to achieve because the current demographic techniques do not provide reliable results (Keyfitz, 1996 as cited by Booth, 2006).

III.5.5 *Scale*

As already discussed in Section III.4, environmental change occurs across multiple scales and multiple levels. Exclusively researching one scale will result in limited knowledge on the complexities and dynamics of drivers of environmental change. In addition, the environmental problems resulting from human activities go beyond all political and organizational levels and yet, most often, scale coincides with social organizational levels (Biggs et al., 2007; Gibson et al., 2000). One of the most pressing challenges facing researchers in this domain is to develop formal approaches to reduce the inconsistencies in modelling scales. Currently, a precise approach to linking scenarios across multiple scales does not exist and what is credible at one scale is often lost at another scale (Biggs et al., 2007; Verburg et al., 2004). Researchers need to understand to what extent scale dependencies in drivers are important and to evaluate the purpose of creating linkages across scales (Biggs et al., 2007; Verburg et al., 2004). Regional scenarios are developed with little or no reference to global scenarios but yet, are applied to them, resulting in a substantial degree of inconsistency (Biggs et al., 2007). Household level provides a better insight of land use drivers, human behaviour and decision-making processes compared to the broader spatial scales, but lack the relation between the household and the biophysical environment. Thus, household level studies disregard the spatial nature of the problem (Geoghegan et al. 1998 as cited by Overmars and Verburg, 2005). To overcome this specific obstacle, the process referred to as 'socializing the pixel', which combines household level data directly to the pixels in remote sensing images, is recommended (Geoghegan et al. 1998 as cited by Overmars and Verburg, 2005). Additionally, no common definitions for scales and levels exist and are often used interchangeably, thus resulting in a lack of clarity (Gibson et al., 2000).

III.5.6 *Investigation of the problem*

Collecting data on indirect drivers such as culture, religion, values, and behaviours, is not as easy as collecting data on population and economic variables. It is an enormous challenge to identify, measure, and monitor the influences of social and cultural indirect drivers on the environment. The same challenges apply to direct drivers such as war or militarism. Scientists investigate only what can be measured and are often oriented towards measuring patterns of behaviours (Redman, 1999). The problem may not be entirely captured as a result of this.

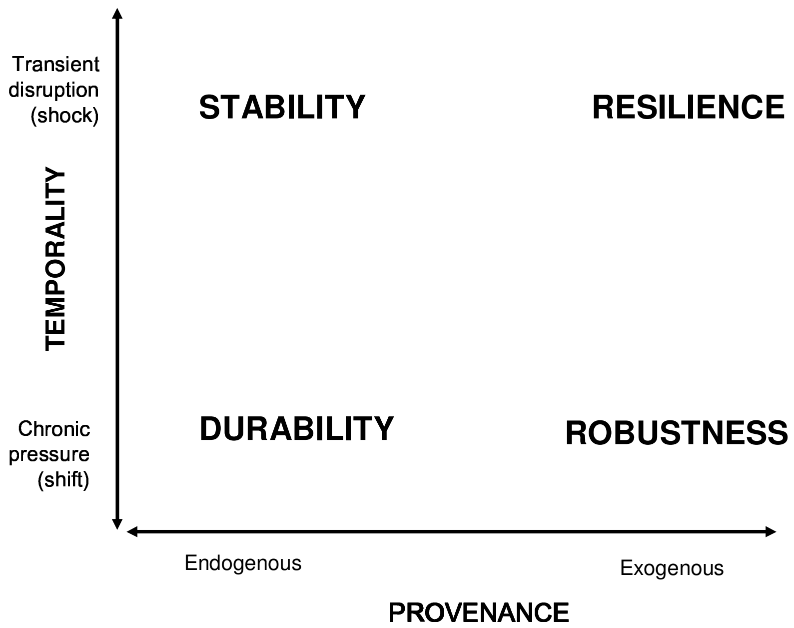
III.6 Conceptualization of drivers: A case study

The DPSIR analytical framework (presented in Section II.4.1) is widely used to conceptualize information on the impacts of human activities on ecosystems. Although it has been commended for its simplistic ability to illustrate complex problems in a comprehensible way, it has also been criticized for its lack of spatial and temporal dimension and for its static and linear relation between elements (driving forces, pressures, states, impacts and responses). A consensus is emerging for the need to look for broader approaches and solutions in order to achieve a greater understanding of drivers of environmental change (Berkes et al., 2003). This is due to the reality that many of the resource and environmental problems are proving resistant to human solutions and a gap has developed between these problems and societies' abilities to address them (Berkes et al., 2003). Within any framework, alternative approaches and elements can be applied as the purpose of a framework is to provide a means to conceptualizing a phenomenon. In efforts to expand upon the DPSIR framework, this project sets out to link the concepts of the social-ecological systems (SES) to the DPSIR framework.

The SES, also known as socio-ecological systems (Gallopin et al., 1989) and coupled human-environment systems (Turner at al., 2003), are complex adaptive systems that link social systems (such as property rights, land tenure, and knowledge) and natural environments (or ecological systems) for the investigation of the complex interactions between these two systems (Berkes and Folke, 1998; Janssen and Ostrom, 2006). The underlying view shaping this framework is that social and ecological systems are interconnected, co-evolving across spatial and temporal scales, and the boundaries between these systems are arbitrary (Berkes and Folke, 1998; Folke, 2007). These two systems are complex in themselves and it is an enormous challenge to investigate the interactions between them (Berkes et al., 2003). The attributes of complex systems include nonlinearity, uncertainty, emergence, scale and self-organization (Berkes et al., 2003). *"Nonlinearity is related to inherent uncertainty"* (Berkes et al., 2003:5). Complex systems have many possible equilibrium states and are organized around one of these possible states (Berkes et al., 2003). Albeit, when a complex system's conditions changes, it can maintain its current state up to a critical level of change (Berkes et al., 2003). Resilience, considered an emergent property of complex systems, absorbs disturbances and provides an adaptive capacity to change, as defined in further detail below (Berkes et al., 2003). To research the interdependencies between social and ecological systems, the dimensions of time and space need to be defined (Carlsson, 2003). The choice of scale affects the type of patterns that will be observed (Gibson et al., 2000). Complex systems are linked to many subsystems of which many are hierarchical (Berkes et al., 2003). For instance, a small watershed ecosystem is part of a larger watershed ecosystem and is part of an even larger watershed, which includes all the smaller watersheds. The self-organization of complex systems will occur at critical points of instability, at which points the system may branch into one of a number of states (Berkes et al., 2003).

The framework, as developed by Stirling (2007), illustrates the complexity of the interdependencies between social and ecological systems in relation to the concepts of resilience, stability, durability and robustness, and how indirect and direct drivers are related to temporality and provenance (see Figure 2). This framework is in the explorative phase. *Resilience* is currently defined as *"the capacity of a system to absorb disturbances and re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks"* (Walker et al., 2004 cited by Folke 2006). In Stirling's (2007) framework, resilience absorbs transient and exogenous disruptions to the defined system. *Stability* is a system's resistance or tolerance to transient and endogenous changes (Dawson and Ingram, 2007).

Figure 2: Sustainable properties of complex dynamic systems.



Adapted from Stirling, 2007

The difference between stability and resilience is that stable systems tend to return quickly to equilibrium after a temporary disturbance whereas resilient systems may not have a single point of equilibrium (Holling 1973 as cited by Davidson-Hunt and Berkes, 2003). *Durability* refers to a system's ability to resist wear and decay from chronic and endogenous disturbances and to maintain the social-ecological functions over a long period of time (Dawson and Ingram, 2007). The meaning of robustness is still under debate within the social-ecological research domain (Young et al., 2006). *Robustness,* in this report, refers to the structural and relevant properties of a system that enables it to withstand or cope with chronic and exogenous disturbances without changing the system's structure (Dawson and Ingram, 2007; Anderies et al., 2004 cited by Young et al., 2006). The concepts of resilience, stability, durability and robustness can only be understood in relation to one another (Stirling, 2007; van der Leeuw cited by Young et al., 2006). However, each term refers to quite fundamentally different conditions and trigger different responses (personal communication with Andy Stirling, September 2007). The temporality of drivers is categorized into two classes in Stirling's framework: chronic or transient. The provenance of drivers is categorized into two classes: endogenous and exogenous. Endogenous disturbances are internal to the defined system itself and exogenous disturbances are external to it.

III.6.1 *Objectives*

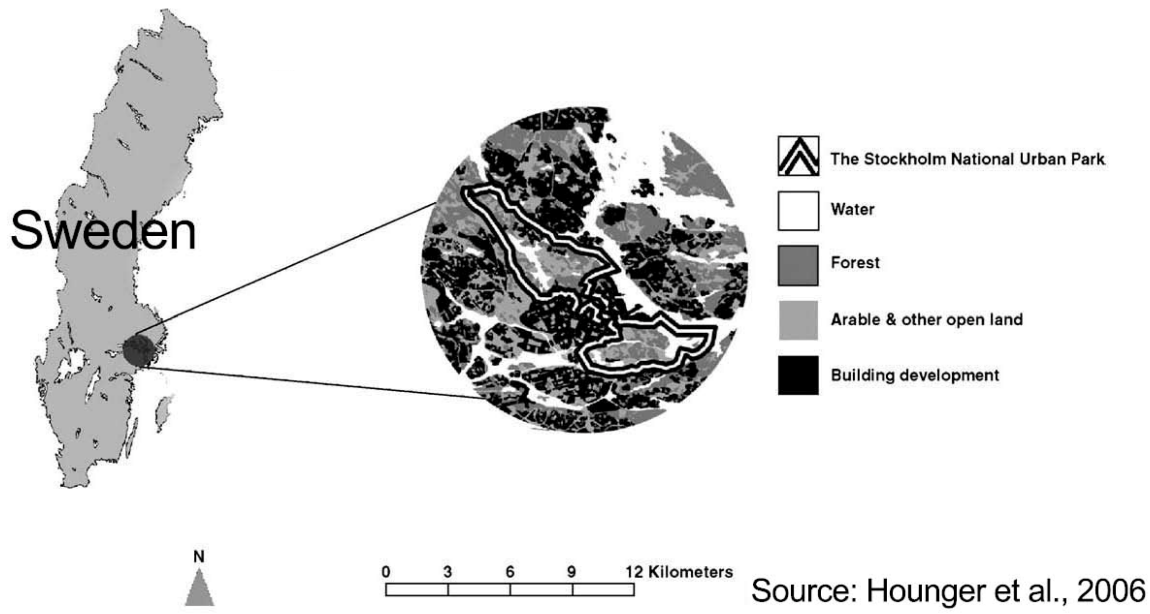
The new DPSIR-SES framework is applied to a defined ecosystem service and a selection of drivers to investigate the following:

- What sustains the defined ecosystem service?
- Which factors could change the functioning of the defined ecosystem service?

Background to the case study

The Stockholm National Urban Park (NUP) in Sweden is located next to the inner city area of Stockholm, situated between Lake Mälaren and the Baltic Sea (Barthel et al., 2005) (Figure 3). The area of the park (27 km^2) is divided between three municipalities and borders with four other municipalities (Barthel et al., 2005). Humans have been transforming this region since the Bronze Age (Barthel et al., 2005). Up until the end of the 1600s, agriculture was the dominant land use in this area and the forests were in poor condition (Herdin, 2002 cited by Barthel et al., 2005). By the end of the 1600s, the nobility built their houses in Stockholm and consequently, did not cut the oak trees located on their estates as nature symbolized power and status (Barthel et al., 2005). This changed by the end of the next century and deforestation took place as a result of intensive grazing in that region, the demand of wood for heating purposes and wood theft (Barthel et al., 2005). The concept that 'nature is divine' emerged during the 1700s and counteracted deforestation (Barthel et al., 2005). Public use of the green spaces in Stockholm occurred as a result of population growth and, in the 1800s, the park became a recreational attraction. An amusement park, theatres, and museums were established, which was a common trend in several European cities during that time. With the rapid growth in urbanization at the beginning of the 20th century, parts of the park were transformed into residences and buildings. However, in response to local campaigns to stop destruction of the park, the parliament developed a law to protect the park in 1995 (Barthel et al., 2005). This area is now governed under the Swedish Environmental Code as an area of national interest and has become the first national urban park in the world (Barthel et al., 2005).

Figure 3: Stockholm National Urban Park.



Ecosystem service: oak seed dispersal by jays

The ecosystem service is the oak (*Quercus robur* and *Quercus petrea*) seed dispersal provided by the Eurasian jays (*Garrulus glandarius*), hereafter referred to as jay. A jay hides 4500 to 11000 acorns a year, some of which are consumed (~37%) and others which are not (~63%) (Hougner et al., 2006). Out of the acorns that are not consumed (the 63%), 50% will develop into saplings (Hougner et al., 2006).

Importance of oak seed dispersal

The importance of this ecosystem service within the NUP primarily includes the regeneration of oak trees, the continuation of gene flow, and food (e.g. acorns) for animals. Moreover, oaks are a major keystone species[8] in the hemiboreal forest zone and provide niches for flora and fauna as well as host up to 1500 species of insects, mosses, fungi and lichens (Hougner et al., 2006). This ecosystem also provides various benefits to humans, including provisioning services, regulating services, cultural services and supporting services. The MA defines cultural services[9] as *"the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences"* (Carpenter et al., 2005:29). As the oak trees in this location have no commercial use, but have cultural and aesthetic attributes, they are thus classified as cultural services. If these oak trees were located in a different location, as opposed to in a secured park, this ecosystem could provide such factors as fuelwood or timber and would then be a provisioning service[10]. Finally, the economic costs to replace this service by a man-made substitute would be approximately 35.500 UK Stirling per annum (Hougner et al., 2006); therefore,

[8] Keystone species are those whose impacts on their ecosystem are large and if removed, dramatic changes to the ecosystem would result (Paine, 1966, 1969 as cited by Hougner et al., 2006).
[9] For the other types of ecosystem services, see definition for ecosystem services in the glossary.
[10] Provisioning services are the products people obtain from ecosystems, such as food, fuel, fiber, fresh water, and genetic resources (Carpenter et al., 2005:29).

the current oak seed dispersal ecosystem service functions are more cost efficient to maintain and manage than to replace.

III.6.2 *What sustains the defined ecosystem service?*

In this section, the components that sustain the defined ecosystem service are explored through the integrated DPSIR-SES framework. Figure 4 presents the DPSIR framework together with the SES boundary. The DPSIR elements have been slightly modified and definitions are provided below. The terms *driving forces* and *pressures* will be used in this context to compliment the DPSIR framework as opposed to *indirect* and *direct drivers* used throughout the rest of this report. Each element is discussed below, followed by a summary of the components that sustain the oak seed dispersal system.

The **driving forces** are the natural or anthropogenic factors, *exogenous* to the defined system, as displayed in Figure 4, which indirectly cause a change to the ecosystem (MA definition). Generally, responses feed back to pressures, but in certain circumstances, they can link to the driving forces. The following driving forces are identified based on their frequency presented in the matrix (Table 3 in Section III.2) and from the relevant literature:

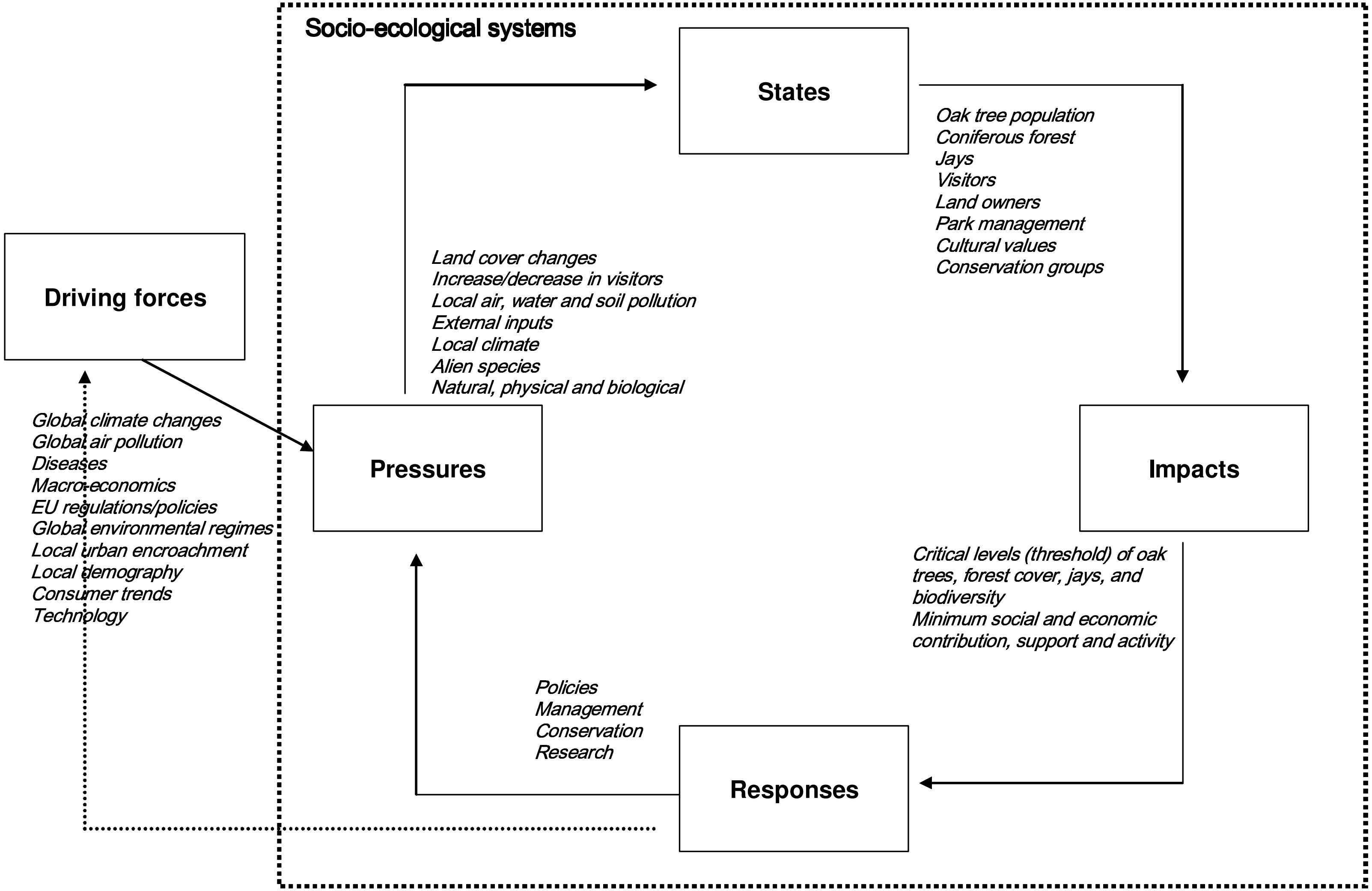
- Global climate change
- Global air pollution
- Diseases
- Macro-economics
- EU regulations / policies
- International environmental regimes (e.g. Kyoto Protocol)
- Local urban expansion / encroachment
- Local demography
- Consumer behaviour and trends
- Technology

The listed driving forces do not all share the same degree of influence and some are long-term concerns (e.g. global climate change) whereas others are prevalent in the immediate future (e.g. local urban encroachment). Presently, urban encroachment is considered one of the most serious driving forces of the NUP and is directly linked to the continual growth of the metropolitan area of Stockholm (Barthel et al., 2005).

The **pressures** are the physical, biological or chemical processes, *endogenous* to the defined system, which tend to directly influence changes in the oak seed dispersal ecosystem service (MA definition). The following pressures are identified based on their frequency presented in the matrix (Table 4 in Section III.3) and from the relevant literature:

- Land cover changes (building of roads, housing, etc.)
- Increase or decrease in visitors
- Local air, water and soil pollution
- External inputs (e.g. fertilizers / pesticides)
- Introduction of new species
- Local climate and extreme climatic events
- Natural, physical, biological (e.g. volcanoes, evolution) phenomena

Figure 4: DPSIR – SES framework for the oak seed dispersal ecosystem service.



As with the driving forces, the listed pressures do not all share the same magnitude and scale of influence on the oak seed dispersal ecosystem service. Some pressures occur over long-term temporal scales (e.g. evolution, local climate) while others may have immediate impacts (e.g. land cover changes).

The **state** of the social and ecological systems refers to the quantifiable and qualitative physical, biological and chemical conditions in the defined system (Gabrielsen and Bosch, 2003) and determines the sensitivity of the system to the pressures. The oak tree population began in the 18th century, according to the historical ecological records, and has become one of the largest oak forests in Sweden. As well, it has the largest population of giant oaks in Europe (Hougner et al., 2006). On average, 18%[11] of all trees found in the park are oak trees, some of which are 500 years old (Hougner et al., 2006). An oak tree can live up to around 200 years or more. Approximately 85% of the oaks in the NUP are a result of natural regeneration, which is primarily dependent on the 84 jays in the park (Hougner et al., 2006). As mentioned above, a jay hides 4500 to 11000 acorns a year, some of which are consumed by the jays, roe deer (*Capreolus capreolus*) and wood mice (*Apodemus flavicollis*), and the other acorns are hidden (Hougner et al., 2006). The red squirrel (*Sciurus vulgaris*) and the wood mouse also contribute to the seed dispersal of oak saplings in the NUP, but the jay is the controlling factor in oak tree regeneration and its existence determines the resilience of the forest (Berkes et al., 2003; Hougner et al., 2006). Jays require densely populated coniferous forests in order to breed and a coniferous forest exists in the NUP and surrounding areas (Hougner et al., 2006). Oak trees also contribute to their own regeneration during the fall months when their leaves shed and cover the majority of the acorns that have fallen. In addition, this park has a high level of biodiversity, which is an essential component of the self-organizing attribute of complex systems (Levin, 1999 as cited by Folke, 2006). The self-organization of a defined system is linked to the existence of species groupings or functional groups (e.g. predators, herbivores, pollinators) in terms of the system's ability to absorb disturbance, and to re-generate and re-organize the system following disturbance (Folke et al., 2004 as cited by Folke, 2006).

Humans have played a dominant role in shaping the land and securing such rich biodiversity in this region. The current state of the park's biodiversity is the result of long-term management. The Royal Djurgården Administration (RDA) was established in 1680 to manage the park and it still manages 80% of the park today (Barthel et al., 2005). Oak trees have intentionally been favoured throughout the years and the established long-term management policies have set out to ensure the secure and sustainable growth of these trees (Barthel et al., 2005). The sustainability of the oak ecosystem most likely has occurred with the improved understanding of this ecosystem (Folke et al., 2003). The dominant landowners include the Swedish State, the RDA, two real estate companies, and the municipalities of Stockholm, Solna and Lidingö (Barthel et al., 2005). Additionally, under the non-profit association, Alliance of the Ecopark (http://www.ekoparken.org/), established in 1992, there are more than 50 organizations representing 175,000 members involved in the management of the park (Barthel et al., 2005). The Word Wild Life Federation is amongst the organizations, adding international importance to the park. More importantly, the dominant landowners and stakeholders of NUP are members of the alliance. The involvement of locals in making managerial decisions about the park ensures those with the highest interests in the park will benefit from the decisions, which in turn, leads to a robust system (Anderies et al., 2004).

Cultural values are the foundations of decision-making (Lambin et al., 2003), which is apparent in the development of the NUP. Nature is highly valued by the local society. During the 1960s and

[11] Barthel et al. (2005) states that approximately 25% of all trees are oak trees in NUP.

1970s, an environmentalist movement developed, which carried on into the 1980s, and has grown even stronger in recent years (Lundqvist 1971 and Boström 2001 as cited by Barthel et al., 2005). The park is highly valued for its recreational and cultural services and is the most visited destination in Sweden, with 15 million visitors per year (Barthel et al., 2005). The appreciation for nature is not a new concept to the area and has influenced the land use choices in the region as early as the royal hunting period in the 1600s. Decisions concerning sections of this area have been primarily based on the intrinsic value of the ecosystem.

Social memory plays an important role in enhancing resilience and a reduction in social memory can cause an increase of changes in the stability of the defined system (Folke et al., 2003). Social memory, defined by McIntosh (2000), is *"the arena in which captured experience with change and successful adaptations, embedded in a deeper level of values, is actualized through community debate and decision-making processes into appropriate strategy for dealing with ongoing change"* (as cited by Folke et al., 2003:367). Social memory consists of individuals, institutions, organizations and other players that have diverse, but in some instances overlapping, roles within and between critical functional groups (Folke et al., 2003). There are local stewardship and conservation groups, authorized users, managements, owners, and visitors that take great interest in the conservation of this park and influence the community debate and decision-making processes (Barthel et al., 2005). In addition, the long-term management of the RDA has led to an accumulation of information and records about the park and ongoing changes, which has facilitated the development of appropriate management strategies and techniques.

The **impacts** are the changes in the ecosystem service conditions or in social systems, which affect the social, economic and environmental domains and result from changes in the state (Gabrielsen and Bosch, 2003). The underlying assumption of the DPSIR framework is that the impacts pose negative effects but this is not always the case in social-ecological systems. These changes occur at critical levels, or thresholds, which are generally unknown and the degree of impact is dependent on the system's vulnerability. *"Vulnerability is the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor"* (Turner et al., 2003). In vulnerable systems, even the smallest disturbances can cause dramatic social, economic and environmental consequences (Adger, 2006 cited by Folke, 2006).

In the present state, this ecosystem service is not in a vulnerable state as there is a substantially large amount of oak trees in the park and these trees have developed in a secure environment, providing them with ample space and time for growth. An adequate number of jays exist in the forest, which contributes to the dispersal and planting of acorns. In addition to jays, there are secondary contributors (e.g. mouse and squirrel), as discussed above, which also assist to a lesser degree with this service. The long-term management and cultural values of the people contribute to the sustainability and stability of this park. In the next section, changes in the social-ecological systems will be discussed along with plausible corresponding impacts.

Responses are the actions carried out by society and governments in efforts to minimize the negative impacts but can also maximize the positive effects on the environment. Policies are developed to prevent, ameliorate or adapt to the changes of the ecosystem (Gabrielsen and Bosch, 2003). The city had planned to develop housing in part of the park due to a high demand for urban housing; however, the local society campaigned against this decision. In 1995, in response to the campaigns, the parliament passed a by-law, the Swedish Environmental Code, to protect the park which, at the same time, gave it national status (Barthel et al., 2005). New development is permissible in the park under the stipulation that it does not interfere with or cause harm to the park's landscape (Rubenson, 2000 as cited by Barthel et al., 2005). There are several conservation groups and local stewardship associations which have taken a strong interest in the conservation of the NUP and participate in activities such as oak planting projects and restoration of water bodies (Barthel et al., 2005). Another notable social response is that the NUP is an area of research interest of the Millennium Ecosystem Assessment[12] due to its high level of biodiversity and oak tree population.

The sustainability of the oak seed dispersal system

The sustainability of this ecosystem service is dependent on the dynamic relationships between the optimal biophysical conditions (e.g. right temperature, sufficient rainfall) for oak regeneration, an adequate jay population and the critical conditions to preserve the jays (e.g. densely coniferous forests and a non-threatening environment). The oak trees are part of the NUP where the social systems have positively contributed to the development, maintenance and security of the oak seed dispersal ecosystem service as well as ensuring optimal conditions for growth. Characteristics of the social systems which have had a dominating role in shaping the park include long-term management, public and private property ownership, knowledge about biodiversity and landscape, cultural values and policies.

Sustainability is linked to the effective understanding of the interdependencies of the social-ecological systems (Stirling, 2007). For this system to function in a sustainable manner, the essential attributes of the four components: resilience, stability, durability and robustness, must be exhibited (Dawson and Ingram, 2007), yet the sustainability of each component of the defined system is as important, or debatably more so, as the sustainability of the overall social-ecological system (Stirling, 2007). Based on the available information on this park, the state of the ecosystem service of oak seed dispersal is a highly stable, durable, robust and resilient system as it stands today.

Sustainability is an ongoing process of change. Social and ecological systems have links across temporal and spatial scales and decisions in one place may affect people in another place (Gunderson and Holling, 2002 cited by Folke, 2007). This is evident in the case of the NUP. The affluent societies have had a dominating role in shaping the landscape. The royalty and elite made various decisions on the management and conservation of this region between the 15th and 18th centuries and, prior to the 18th century, ordinary citizens were prohibited from entering this area (Barthel et al., 2005). During the 1800s, King Gustav III and Israel af Ström, the chief forest officer at that time, took great care in enhancing the landscape by planting various local and exotic species and there was a particular interest in oak trees (Barthel et al., 2005). The characteristics of the park today are strongly linked to their involvement (Lange, 2000 as cited by Barthel et al., 2005). The affluent societies, who made the decisions on the landscape over the centuries, had the financial luxury and social status to appreciate the land for its intrinsic value and not its instrumental value, to purchase and plant a number of local and foreign species, and to manage and maintain it. The park may not have been as it is today if farmers, shipbuilders, and other labour groups, dependent on the land to sustain a living, had dominated the land use decisions.

III.6.3 *Which factors could change the functioning of the defined ecosystem service?*

Change is assumed to explain stability as opposed to assuming stability to explain change (van der Leeuw, 2000 as cited by Berkes et al., 2003). To conceptualize the assumed changes of the oak seed

[12] http://www.millenniumassessment.org/en/SGA.SwedenStockholm.aspx

dispersal ecosystem service, the driving forces and pressures are categorized into the following: endogenous or exogenous, and transient or chronic (Stirling, 2007) (see Figure 5). By categorizing the driving forces and pressures as mentioned, it emphasizes which of the driving forces and pressures can be controlled within the defined system. In addition, it defines which components of the system cope with the relevant driving forces and pressures. The temporal scale of analysis is the present up to the year 2100, which is just over the 'medium run period of one generation', as distinguished by Daly (1987), and the spatial scale is the NUP.

The transient and chronic exogenous driving forces and the transient and chronic endogenous pressures are discussed in relation to the four concepts of the SES to understand the dynamic processes and changes. Each concept is viewed to some degree individually, yet not exclusively, as they are interdependent and necessary individually and collectively to achieve sustainability (Stirling, 2007 as cited by Darwin and Ingram, 2007). In this section, only select driving forces and pressures will be discussed.

Exogenous driving forces

Resilience in the oak seed dispersal ecosystem deals with the driving forces categorized as exogenous and transient to the defined system, which include the introduction of alien species, disease, macro-economics, EU regulations, and consumer behaviour and trends. Resilience is the amount of disturbance the system can absorb and the degree to which the system is capable of re-organization (Carpenter et al., 2001 as cited by Folke, 2006; Resilience Alliance, 2007) as well as the ability to learn from and adapt to disturbances (Carpenter et al., 2001 as cited by Folke, 2006; Resilience Alliance, 2007). To understand how the resilience of the NUP may respond to an exogenous and transient driving force, the case of an intentional or accidental introduction of an alien species will qualitatively be conceptualized.

The introduction of a new species is considered an 'ecological surprise', which is defined as the *"qualitative disagreement between ecosystem behaviour and a priori expectations – an environmental cognitive dissonance"* (Gunderson, 2003). Brooks (1986) defines three types of ecological surprises: 1) unexpected discrete events, 2) discontinuities in long-term trends, and 3) emergence of new information (as cited by Gunderson, 2003). The first two types of ecological surprises can often be addressed if their occurrences are not ignored and are generally part of a broader-scale process (Gunderson, 2003). For instance, diseases (e.g. oak epidemic, avian influenza, insect viruses) would be classified as discontinuities in long-term trends. This type of ecological surprise deals with abrupt and non-linear, or discontinuous, behaviour of a system and the interactions of variables that occur at different scales (Gunderson, 2003). The emergence of new information is a genuinely new and unique phenomenon and therefore, the introduction, or invasion, of an alien species (e.g. alien trees, fauna) would fall within the third category. The introduction of an alien species would not necessarily cause a collapse to a system and it is not always considered negative. There have been many cases of successful introductions of species into undisturbed ecosystems (McNeely et al., 1995). The key to resilience in social-ecological systems is diversity, but not specifically the number of species (Folke, 2006; Resilience Alliance, 2007). The NUP hosts 75% of all species in Uppland, Sweden (12 800 km^2 area), and it is rich in terms of biodiversity (Barthel et al., 2005). Species that may appear redundant and unnecessary, at a critical moment of change, may become important to the ecosystem service (Folke, 2006). If a new species is introduced, the resilience of the oak seed dispersal system in its current status would temporarily absorb the disruption and re-organize the ecosystem service to a stable state again (see Figure 6).

Figure 5: Sustainable properties of the DPSIR – SES framework in terms of their temporality and provenance.

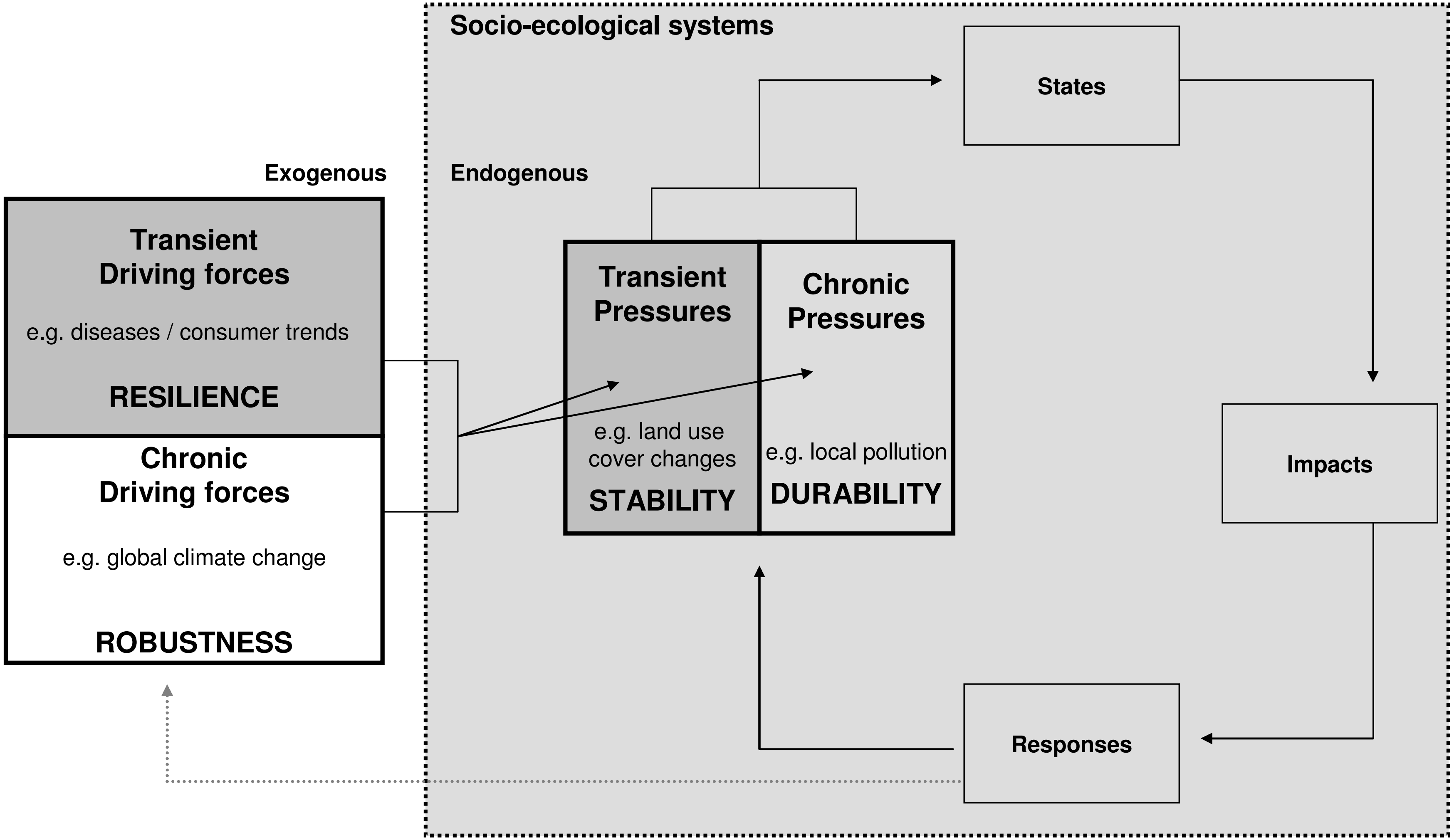
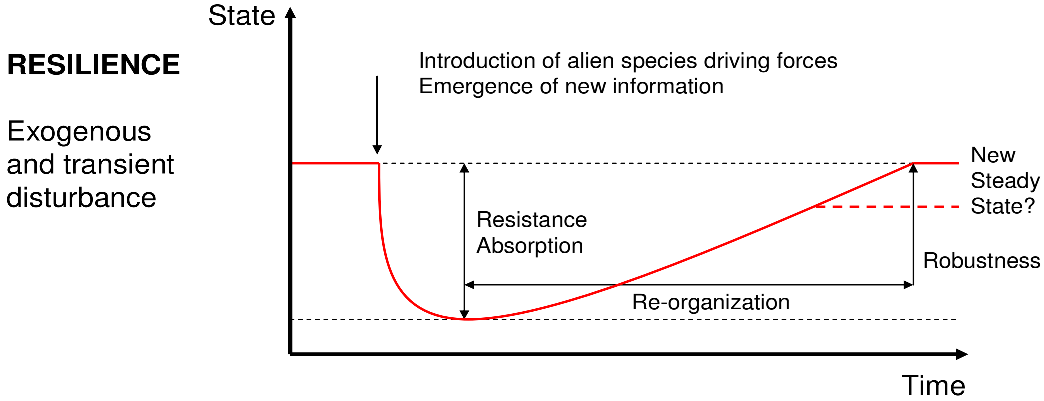


Figure 6: Introduction of alien species and resilience (adapted from electronic presentation by Dawson and Rounsevell, 2007).



The loss of resilience is also linked to inflexibility of institutions and policies (Gunderson, 2003; Resilience Alliance, 2007). The response of the park management to the new invasion will either cause an increase or decrease in the resilience of the ecosystem (Gunderson, 2003). Where flexibility in policies exists, exogenous disruptions can be managed without a change in current policies (Gunderson, 2003). Ecological surprises that become ecological crises are linked to limitations and failures of policy (Gunderson, 2003). Social systems have to cope with uncertainty as surprises are the norm.

Economic growth can contribute to enhancing environmental protection measures and to improving environmental quality (Nelson et al., 2005). Affluent societies seek to improve their quality of life and their living environments, and policies and regulations are developed to meet these goals (Nelson et al., 2005). Sweden is a developed country in the European Union and PPP (Purchasing Power Parity) GDP (Gross Domestic Product) is 318,069 US $ for 2007 (World Bank, 2007). The robustness of the defined system copes with the gradual macro-economic increases or decreases while the resilience deals with the drastic fluctuations linked to factors such as currency exchange rates, product prices, consumer and market behaviour.

In the oak seed dispersal ecosystem, the exogenous and chronic driving forces which interact with the **robustness** component include global climate change, global air pollution, local urban encroachment, local demographic components, technology and international environmental regimes. In systems where components have been intentionally designed, as with the oak trees in the NUP, robustness may be more applicable to the functioning of the system as opposed to resilience (Carpenter et al. 2001 as cited by Anderies et al., 2004). The past social-ecological interactions within this defined system are important when assessing the robustness of the system (Anderies et al., 2004). The definition for robust is, *"powerfully built; sturdy; healthy"*[13]. A robust system prevents the ecosystem on which it is dependent from shifting into another state. If one part of this ecosystem service collapses, for instance, all jays die due to a sudden disease, does that cause the system to lose its robustness? This answer is linked to the temporal scale of analysis. The temporal scale of analysis in this situation is a period of one generation (Daly, 1987). Therefore, the removal of jays will almost certainly not affect the oak trees during this timeframe. The jay provides resilience to the ecosystem service whereas the long-term management provides robustness to the oak (and coniferous) trees. There are a large number of oak trees in the NUP and these trees will continue growing for hundreds of years under the assumption that conditions remain

[13] http://dictionary.reference.com/browse/robustness

similar, even without the jays. The regeneration process may decline, but not as rapidly as a non-robust system might, due to the absence of jays throughout the years, and it may not become obvious until well into the future. If it reaches a critical threshold where the system "collapses", it will re-organize by shifting the role of other species that did not contribute to this ecosystem service to suddenly play an important role (Folke, 2006).

The long-term management of the park has led to the development of the oak population. Under the assumption that the future society and management value oak trees to the same degree as today's society, the response of the park management will then be to ensure the regeneration process is occurring at a similar speed and level as it is today. A response may be to replace this service by a human-made substitute or to re-introduce jays into the park and monitor the performance of the selected response.

To understand how the robustness of the NUP may respond to an exogenous and chronic driving force, the local driving force of urban encroachment will be conceptualized. Currently, urban encroachment is a persistent driving force of the NUP (Barthel et al., 2005). An increase in the local population has influenced an increase in the need for housing. A policy was established in 1995 to protect the park and prevent urban development in and around the park. The enforcement of this policy has been effective in preserving the park since new development inside the park has not taken place since it was passed. If an increase in urban growth around the park continues, this may cause an increase in local air pollution. More importantly, the demand for additional housing may become so persistent that the government may be forced to meet this emerging need. The economic benefits may outweigh the cultural benefits of the park if the demand escalates.

The driving force of urban expansion and encroachment may result in land use change pressures, causing a large area of the park to be transformed into residential housing and roads, which would influence the stability of the system. The development of new housing could cause a loss to part of the ecosystem, meet the needs of the growing urban population and create a higher economic value and cultural appreciation for the reduced green space.

Endogenous factors

The endogenous and transient pressures which interact primarily with the **stability** component include extreme local climatic events, land use cover changes, natural, physical and biological (e.g. evolution) phenomena. The definition for stability is, *"resistance to change, especially sudden change or deterioration"*[14]. To understand how the stability of the NUP may respond to an endogenous and transient pressure, the local climatic event of fire will be qualitatively conceptualized. Fire is a natural and important phenomenon in many forests, including the boreal and boreo-nemoral zones where most of Sweden lies (IFFN, 2004; UNEP-GEO, 2002). Gunderson (2003) classifies fires as an ecological surprise of discontinuous behaviour in long-term trends, which is the second type of the three ecological surprises as mentioned above (see resilience in exogenous driving forces). Fires fall into this classification since they have an abrupt and nonlinear behaviour to the social-ecological system. Once the analysis of a fire's occurrence has been conducted, it can be linked to variables that operate at different scale ranges (Gunderson, 2003). For instance, local fires can be interconnected to the indirect drivers of global climate change or land clearance. Forest fires that occur as natural phenomena have a frequency of occurrence, which takes place in yearly intervals, and if attention is given to this occurrence, can be recorded and monitored. In Sweden, fires occur every 50-150 years in the north and every 20 years in the south (Page et al.,

[14] http://dictionary.reference.com/browse/stability

1997 cited by IFFN, 2004). This information is recorded and archived in Sweden and can prove essential to sustaining institutional memory. Institutional memory, as defined by Folke et al. (2003), is a collective memory of experiences which provide the framework for social response to change (e.g. fire) while also contributing to flexible and adaptive management. Through the sustainability of institutional memory, the ecological surprise of fire is manageable and will not shift to an ecological crisis. Stability is lost only if a failure occurs in the management system. The NUP management has developed strategies and policies to cope with fire, such as having a fire station just outside the park, trained fire fighters and appropriate roads and fire hydrants throughout the park.

Fires are also used as a mechanism to intentionally change temporal and spatial characteristics of land cover and uses (Davidson-Hunt and Berkes, 2003). Through the intentional use of fire as a mechanism of land use change, humans aim *"to gain stability by reducing the size of the stability domain"* (Davidson-Hunt and Berkes, 2003:67). This results in a reduction in resilience but a short-term increase in stability (Davidson-Hunt and Berkes, 2003). Important to note is that by creating small-scale fires, the effects of large-scale fires on ecosystems may be reduced (Davidson-Hunt and Berkes, 2003).

Durability of the social-ecological system copes with the endogenous and chronic pressures (Stirling, 2007), which include external inputs, local pollution, local climate, and the fluctuation of visitors to the NUP. To examine the durability of the NUP, increases and decreases in visitors will be qualitatively discussed. An estimated 15 million visitors enter the park each year and if an assumed uncontrolled increase in this number occurs, it may have a negative impact. More visitors could lead to an increase in local air pollution from the additional number of cars and buses travelling to the park. As well, an increase in noise pollution and damages to the park grounds may occur as more people would be walking through the park. If the pressures from the uncontrolled increase of visitors reach a critical point where the negative impacts cause substantial degradation to the ecosystem service, it will feed into the response element of the DPSIR-SES framework. The park management may respond by developing strategies to counteract these disturbances as to ensure the durability and stability of the system is not lost. Strategies could include zoning off areas to cars and developing shuttle bus routes, adding additional bins in the park, restricting people to walk through non-sensitive areas of the park, creating information brochures about the park's importance, restricting the number of visitors and charging an entrance fee to all visitors.

Visitors could also be considered a positive pressure. People visit the park because of their high value for green spaces and to enjoy the various recreational activities (e.g. amusement park, theatre) in the park. If the number of visitors start to decline, this may pose a negative impact as it could imply that people do not value the park to the same degree as before and a shift in recreational activities has occurred. It could also result in a weakening of the conservation groups, which may grant the government the liberty to change the current land cover to something of more value to the people (e.g. housing).

The durability of the system in relation to the pressures of external inputs will be discussed as well. External inputs, such as fertilizers and pesticides, may be applied in the NUP by the park management to protect and enhance growth of park species. Often external inputs may impact non-target organisms such as birds and people. Birds are more susceptible to fertilizers and pesticides due to their lack of detoxifying acetylcholinesterase activity and have low microsomal monooxygenase detoxifying activity in the liver (Walker as cited by Brasel et al., 2007). Birds can be exposed to external inputs directly or indirectly by consuming contaminated prey (e.g. insects) (Pimentel et al., 1992). Assuming external inputs are applied on a regular basis in accordance with regulations, the durability of the social-ecological system must cope with this chronic pressure. Within the timeframe of analysis, decay or collapse to the system would almost certainly not occur due to external inputs. If park management continues to monitor dosages, impacts and research alternative technologies, the durability of the system will not be weakened.

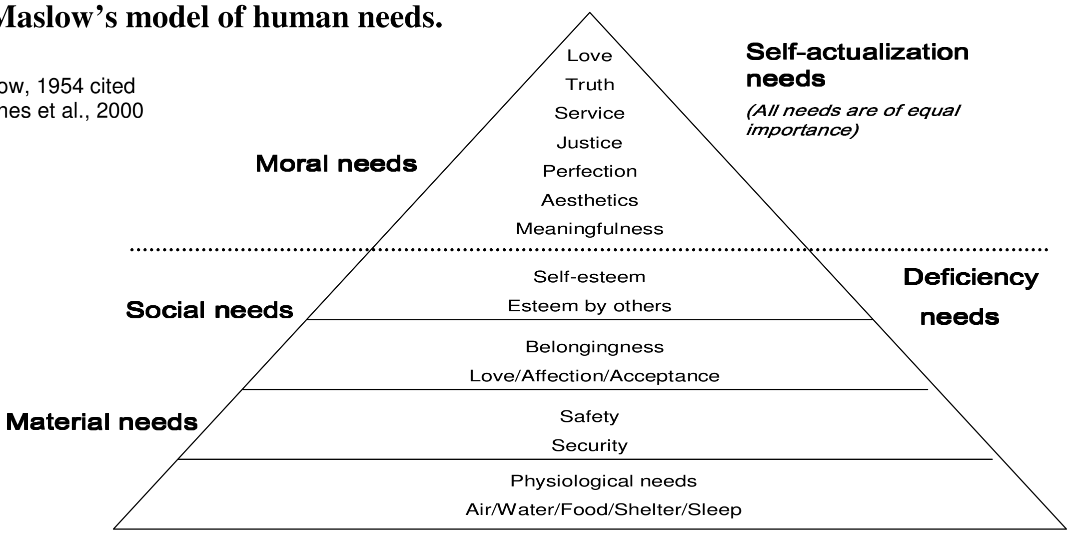
Summary

This new DPSIR-SES framework contributes to achieving a better understanding by uncoupling the dynamics of the defined ecosystem service. By conceptualizing the spatial and temporal nature of driving forces and pressures and identifying the exogenous and endogenous disruptions, the components of the complex systems are illustrated. Durability and sustainability act as the internal components that respond to transient and chronic pressures respectively while robustness and resilience constitute the external components of the social-ecological system and cope with the transient and chronic driving forces respectively. This information can strengthen the response mechanism as social systems will be able to identify, to some degree, whether components are functioning to the required optimal state. This framework also considers social values as state variables, which change with time (electronic presentation by Dawson and Rounsevell, 2007). The dominant influence of the oak seed dispersal ecosystem service that has led to its conservation is interlinked to human decisions and activities that have occurred across temporal and spatial scales.

A benefit of choosing the NUP to apply the DPSIR-SES framework is that there is a clearly defined boundary around the park, which facilitates the establishment of the SES boundary. A good historical ecological record exists which enables a broader understanding of activities that have taken place across temporal and spatial scales. In addition, small-scale governance regimes that incorporate local knowledge, have well-defined and effectively enforced rules, and are dependent on trust, are considered to “perform” well (Ostrom 1990 and Ostrom et al. 2002 as cited by Janssen et al., 2007), which is illustrated through the defined case study. A limitation to selecting the NUP could be that the oak seed dispersal ecosystem service is in a controlled environment, which is visibly dominated by humans. Thus, the example observed is a unique case and may not be applicable in many other settings. Another drawback, but not a limitation per say, is that the defined system is located in an area where the people already highly value the environment. The Swedes are closer to the second level of Maslow’s model of human needs (see Figure 7), and deal with the positive aspects of self-actualization needs, which include moral needs such as truth, aesthetics and justice. If the case study had been in a region where the society was at the lower end, coping with meeting their basic needs (e.g. food, water, shelter), the importance of the oak seed dispersal system would have vastly differed.

Figure 7: Maslow’s model of human needs.

Source: Maslow, 1954 cited in Edward-Jones et al., 2000



IV. CONCLUSIONS

It is difficult to be in the midst of change and to understand it: to separate the deep structures from the shallow constructions, the long rhythms from time's embellishments, or the profound understandings from the current enthusiasm. And we are very much in the midst of change. Kates et al. (1990).

Environmental change research has and continues to significantly contribute to the understanding of structures and functions of the biosphere in relation to change (Turner et al., 2003). The task of identifying change, while in the midst of change, is enormous. This report identifies drivers of environmental change, strengths and research challenges as well as develops a new framework. Important conclusions of this report are synoptically presented below:

- A diverse use of terms and meanings to define drivers of environmental change exists, creating a lack of clarity within this research domain. It is important that researchers define their terms to reduce confusion and facilitate the rapid exchange of comparable information.

- Three dominant sets of definitions for drivers of environmental change have developed over the last decade, namely the LUCC, DPSIR and the MA definitions. These sets of definitions could contribute to reducing confusion if researchers apply these terms and properly reference the definition.

- One common framework does not exist in this research domain. Three frameworks, identified more than once in the literature review, are examined to assess the strengths and limitations. The DPSIR framework is the most commonly referenced framework, followed by IPAT identity.

- Science and technology, and culture and religion are the least discussed indirect drivers of environmental change, while demography, economy and socio-politics are the most discussed.

- Demography is listed as the most referenced and discussed indirect driver of environmental change; however, it is interlinked with economic, socio-political, and cultural and religious indirect drivers, and cannot be examined exclusively. The excessive attention of demography may be embedded in partial factors, such as political or social opinions.

- Land and biodiversity studies address all indirect drivers (e.g. demography, economy, socio-political, science and technology, culture and religion) while the other themes address select indirect drivers.

- Adequate explanation to define the dynamics of indirect drivers has not been reached amongst researchers (Meyer and Turner II, 1992) and it is important to reach a consensus on this issue.

- Direct drivers of land use and cover change, and climate variability and change are the most frequently identified drivers as opposed to the other listed direct drivers.

- Direct drivers of natural, physical and biological phenomena, diseases and wars are the least mentioned and discussed.

- Biodiversity studies address the widest spectrum of direct drivers compared to the other research study themes.

- The classifications of direct drivers are inexplicit in some instances. Specifically, habitat change drivers in essence are the same as land use and cover change drivers. The different use of terms may simply be a difference in perspectives between ecologists and social scientists. In addition, the critical point at which harvest and resource consumption is no longer considered sustainable and thus becomes overexploitation is not defined.

- The majority of studies focus on one spatial scale exclusively yet to understand the problem, a multi-scale approach is needed (Olson et al., 2004b).

- The case study on the oak seed dispersal ecosystem service, conceptualized in the DPSIR-SES framework, presents the links across temporal and spatial scales and how these links have influenced the ecosystem service. The social systems have played a dominant role in the sustainability of this ecosystem service.

- The new DPSIR-SES framework contributes to examining the interdependencies of social-ecological systems evolving across spatial and temporal dimensions whereas the DPSIR in itself allows for an analysis of the effects of human activities on ecological systems and does not consider scales. The delineation of exogenous and endogenous disturbances within chronic and transient temporalities provides a deeper understanding of the system's components: resilience, robustness, stability and durability.

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Appendix I: Literature review results

Table A: Research overview of drivers of environmental change

Author, date, and theme	Definition/ terminology	Framework / scenario applied	Direct drivers	Indirect drivers	Spatial and temporal scale	Findings
Abildtrup et al., 2006 **Theme: Land**	No definitions provided. Global socio-economic drivers: principal factors that influence the evolution of the world in general. Term 'driving forces' used.	Step-wise expert-judgements Four socio-economic scenarios developed: World markets Regional enterprise Global sustainability Local stewardship	Land use: Agriculture	Global socio-economic driving forces for the present and in 2020:[a] ▪ Population ▪ Annual GDP[15] increase ▪ Green GDP variation (ISEW[16]) ▪ GNP[17]/GDP ▪ Social discount rate ▪ Global governance ▪ Local market power ▪ Environmental policy impact ▪ Rural areas development ▪ Climate convention ▪ Equity ▪ Growing sector ▪ Declining sector Agricultural driving forces for the present and in 2020: ▪ CAP[18] market ▪ CAP rural development ▪ Environmental policy pressures ▪ EU enlargement ▪ Resource competition ▪ World demand/supply ▪ World Trade Organization (WTO) role *a: Proposed by ACCELERATES project*	Global, European and regional Present to 2020	▪ In all four scenarios, a revision of the CAP occurs, underlining the progressive reduction in EU intervention in the agricultural commodity markets. ▪ The role of rural development policy has a strong impact in the local stewardship scenario and a low impact in global sustainability scenario. ▪ The enlargement of the EU significantly impacts EU agriculture only in the world market scenario due to increased competition from central and eastern European countries.

[15] GDP: Gross Domestic Product
[16] ISEW: Index of Sustainable Economic Welfare
[17] GNP: Gross National Product

Table A: Research overview of drivers of environmental change

Author, date, and theme	Definition/ terminology	Framework / scenario applied	Direct drivers	Indirect drivers	Spatial and temporal scale	Findings
Alcamo et al., 2006 **Theme: Land**	**Proximate (or direct) causes:** Physical actions on land cover and are usually limited to a recurrent set of activities **Underlying (or root, or indirect) causes:** Fundamental forces that underpin the more proximate circumstances and operate more diffusely often altering one or more proximate causes. *(Definitions taken from Chapter 3, Geist et al., 2006)*	No framework	Land use Land cover change	Demographic ▪ Population size including migration ▪ Size of urban vs rural population Economic ▪ Average per capita income ▪ Biofuels demand[a] ▪ Food demand ▪ Food/crop prices ▪ Food trade ▪ Status of land tenure/farm size[b] Technological and biophysical ▪ Crop yield ▪ Accessibility (infrastructure, travel distance) ▪ Climate ▪ Soil characteristics ▪ Topography Other social factors ▪ Food preferences ▪ Types of governance[b] ▪ Education level[b] *a-typically used only in global/continental scenarios* *b- typically used only in regional and local scenarios*	Global to local scale 2010, 2050 and 2100	▪ Rapid deforestation in Africa and Latin America over the next decade has been presented by regional scenarios. Whereas, within a few decades, global scenarios have presented a slowing of deforestation (linked to the contraction of agricultural land).

[18] CAP: Common Agricultural Policy

Table A: Research overview of drivers of environmental change

Author, date, and theme	Definition/ terminology	Framework / scenario applied	Direct drivers	Indirect drivers	Spatial and temporal scale	Findings
Alcamo et al., 2005 **Theme: Biodiversity**	**Driver**: Natural or human-induced factors that directly or indirectly cause a change in an ecosystem **Direct driver**: Physical, biological, or chemical processes that tend to directly influence changes in ecosystem goods and services **Indirect driver**: Operates more diffusely than direct drivers by altering one or more direct drivers *MA definitions*	Four scenarios: Global Orchestration Order from Strength Adapting Mosaic Technogarden	▪ Greenhouse gas emissions ▪ Air pollution emissions ▪ Risk of acidification and excess nitrogen emissions ▪ Climate change ▪ Sea level rise ▪ Land use and land cover change ▪ Use of nitrogen fertilizers and nitrogen loading to rivers and coastal marine systems ▪ Disruption of landscape by mining and fossil fuel extraction ▪ Energy use	▪ Population ▪ Economic development -Income levels -Economic structure -Consumption -Income distribution ▪ Technological development ▪ Changes in human behaviour ▪ Social, cultural and political	Global and regional scales 2000-2050	▪ Demand for provisioning services increases in all scenarios, increasing stress on relevant ecosystem services. ▪ Land use change is a major driver of changes in the provision of ecosystem services up to 2050. ▪ Climate change and associated impacts are expected to have an increasing effect on the provision of ecosystem services after 2050. ▪ Food supply increases significantly in all scenarios at the global level. ▪ The demand for fish (from freshwater, marine and aquaculture sources) increases in all scenarios
Allan, 2004 **Theme: Freshwater ecosystems**	No definitions provided. Use of terms ‘drivers’, ‘stressors’ and ‘mechanism’	No framework	Direct land use mechanisms influencing stream ecosystems: ▪ Sedimentation ▪ Nutrient enrichment ▪ Contaminant pollution ▪ Hydrologic alteration ▪ Riparian clearing (canopy opening) ▪ Loss of large woody debris		Reach, riparian, and catchment scales	▪ Stream ecosystems are strongly influenced by direct and indirect human action, namely land use, across spatial scales. ▪ Knowledge on how the mechanisms through which land use influence stream ecosystems is limited.

Table A: Research overview of drivers of environmental change

Author, date, and theme	Definition/ terminology	Framework / scenario applied	Direct drivers	Indirect drivers	Spatial and temporal scale	Findings
						▪ The influence of land use operates across all scales, but the response of the variable of concern.
Allen and Barnes, 1985 **Theme: Forests**	No definitions provided. Term 'causes' used.	No framework	▪ Climate ▪ Agricultural expansion (permanent and shifting cultivation) ▪ Commercial logging ▪ Uncontrolled timber extractions ▪ Local fuelwood use ▪ Burning or grazing forests entirely ▪ Illegal cutting and grazing	▪ Population increase and density ▪ Road infrastructure ▪ Forest management ▪ Socio-economic development (population and GNP)	Developing countries	▪ Developing countries with high population growth, expansion of agriculture and high levels of wood production had high rates of deforestation from 1968 to 1978. ▪ Deforestation is linked short-term to rising population and agricultural expansion, and long term to wood harvesting for fuel and export. ▪ High oil prices prevent the poor from using oil instead of wood fuels.
Alter-net R1, 2005 **Themes: Biodiversity and Urban areas**	**Driving forces:** Human activities leading to emissions, resource use and land use creating pressure on nature and the environment **Pressures:** The various anthropogenic environmental pressures resulting from different socio-economic activities of human	DPSIR framework	Pressures of biodiversity: ▪ Climate change ▪ Pollution ▪ Land use change ▪ Harvesting and persecution of species ▪ Introductions of alien species or genotypes	The most important socio-economic drivers of biodiversity: ▪ Demography ▪ Technological changes ▪ Economic growth ▪ Political and social institutions ▪ Culture ▪ Knowledge and information exchange *(cited from Redman, Grove & Kuby, 2004)*	Global	▪ In practice, it is often difficult to distinguish clearly between drivers and pressures.

Table A: Research overview of drivers of environmental change

Author, date, and theme	Definition/ terminology	Framework / scenario applied	Direct drivers	Indirect drivers	Spatial and temporal scale	Findings
	society			Drivers of urban and rural areas: ▪ Demographic changes ▪ Lifestyle ▪ Urban infrastructure ▪ Production, services and technology ▪ Level of wealth ▪ Policy ▪ Attitudes towards nature		
Berge et al., 1997 **Theme: Atmosphere**	**Driving forces:** Societal trends and developments of the main economic sectors **Pressures:** Emission	DPSIR framework	▪ Air pollution ▪ Industry ▪ Energy ▪ Agriculture and forestry ▪ Transport	▪ Population increase ▪ Economy and industry ▪ Transport growth ▪ Tourism	European Union 15 1980-1994	▪ The main trends linked to air pollution problems in EU15 are: population increase, fast growth in air and road transport, continuous growth in tourism, continuous growth in energy consumption and agriculture changes (e.g. change in fertiliser use or livestock increase).
Bidone and Lacerda, 2004 **Theme: Coastal and marine ecosystems**	No specific definitions but terms are derived from the DPSIR framework.	DPSIR framework / Cost Benefit Analysis	▪ Discharge of heavy metals into bay on daily basis ▪ Water pollution and eutrophication	Main driving forces: ▪ Industrial development ▪ Urban development Both of these forces have contributed to: ▪ Population growth ▪ Increase in land occupation for residential purpose ▪ Income levels ▪ Poor policy enforcement	Guanabara Bay, Rio de Janeiro, Brazil	▪ Income level of the population relates directly with the lack of proper sanitary conditions and is directly responsible for the poor environmental quality conditions in which this population lives. ▪ In the study area the GDP fails, since it does not take into consideration the

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						concentration of income and wealth distribution within the population. ▪ The cost to rehabilitate degraded ecosystems has been estimated as 10–50 times higher than the respective prevention costs (World Bank 1992).
Blum, 2004 **Theme: Land**	**Driving forces:** The cause of a certain state of soil. These forces can be cultural, economic, social, technical and ecological. **Pressures:** Mental and physical expression of driving forces (e.g. emission to air, urban expansion, etc.).	DPSIR framework		Cultural, social and economic driving forces of land and soil degradation: *Global level:* ▪ Economic and social theories ▪ WTO[19] regulations ▪ Property rights ▪ Price of energy *National level:* ▪ Market conditions ▪ Transport systems ▪ Social security ▪ Education systems *Local level:* ▪ Land tenure ▪ Family structure ▪ Family income ▪ Health care Ecological and technical driving forces of land and soil degradation: *Global level:* ▪ Climate change	Global, national and local level	▪ DPSIR framework is an effective approach to presenting complex scientific issues in a format that policy makers and stakeholders can understand and process. ▪ Responses should be directed at the driving forces as opposed to remedying the impacts.

[19] WTO: World Trade Organization

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				▪ Change in biodiversity *National level:* ▪ Macroclimate altitude ▪ Topography ▪ Biodiversity ▪ Soil distribution pattern ▪ Technical infrastructure *Local level:* ▪ Microclimate ▪ Topography ▪ Soil quality ▪ Water resources ▪ Biodiversity *Processes are occurring at different temporal scales (short-, medium- and long-term scale).*		
Blum at el., 2004 **Theme: Land**	Definitions are briefly mentioned. Concepts are derived from the DPSIR framework.	DPSIR framework	▪ Emissions to air, water and land ▪ Urban expansion ▪ Infrastructure ▪ Construction ▪ Deforestation ▪ Forest fires ▪ Nutrient mining	▪ Human population ▪ Land development ▪ Tourism ▪ Agricultural production ▪ Transport ▪ Industry / Energy ▪ Mining ▪ Natural events ▪ Climate change ▪ Water stress	NA	▪ Soil research should be connected with other research areas addressing aquatic and terrestrial ecosystems.
Bray et al., 2004 **Theme: Forests**	**Drivers:** Commonly used to refer to the variables that lead to degrading land cover change **Proximate causes of deforestation:** The	Binary logistic regression and multiple regression analysis for impact on land cover	Proximate causes of deforestation from 1984-2000: ▪ Ejido timber volume extraction ▪ Building of new roads and distance to these roads	Driving forces of deforestation from 1976-1984: ▪ Distance to settlements (nearness) ▪ Ejido population (not density) ▪ Ejido age	Santa Cruz Mayan area 1976-1984 1984-2000	▪ Areas within older ejidos (typically larger), and where greater volumes of timber are extracted, are less likely to be deforested. ▪ Landscapes within these

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	immediate local actions, such as agricultural expansion or logging (Geist and Lambin, 2002) **Underlying driving forces of deforestation:** Fundamental social processes, such as population dynamics and institutional policies, which operate at local, national or global levels (Geist and Lambin, 2002) Natural drivers not mentioned.					regions that tend towards sustainability are due to institutional factors. ▪ The existence of a secure land tenure regime from an early period protected these forested areas. ▪ Forest areas that have been intensively used by humans can also show trends toward forest cover stability.
Busch, 2006 **Theme: Land**	No definitions provided. Term 'driving forces' used.	No framework	Agricultural land use and cover change	General driving forces ▪ Demography ▪ Culture and society ▪ Economic development ▪ Technology ▪ Policy and governance ▪ Environment Drivers of demand for agricultural products: *Food demand* ▪ Population growth ▪ Rural population ▪ Migration ▪ Changing age structure ▪ Consumer preferences *Economic development* ▪ Commodity prices	NA	▪ Twenty five scenarios of seven studies refer to demography, culture, society, economic development, technology, policy, governance and environment as driving forces. ▪ Top-down modelling approaches should be accompanied by region-specific bottom-up modelling to strengthen the value of quantitative scenario studies

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Author, date, and theme	Definition/ terminology	Framework / scenario applied	Direct drivers	Indirect drivers	Spatial and temporal scale	Findings
				▪ Economic growth *Policies* ▪ Energy policy ▪ International policies *International Trade* ▪ International trade Drivers of agricultural production: ▪ Crop/livestock production ▪ Technology/ management ▪ Policies ▪ Economy ▪ Biophysical suitability ▪ Spatial restrictions ▪ Nature conservation ▪ Environment ▪ Land use/land cover ▪ Land use mix		
Dale, 1997 **Themes: Land and Atmosphere**	Terms 'cause' and 'consequences' and 'drivers' used.	No framework. Models	Drivers of climate change: ▪ Changes in land cover (e.g. deforestation) ▪ Overgrazing (increases suspended dust) ▪ Release of greenhouse gases	Major drivers of land use change: ▪ Human population ▪ Affluence ▪ Technology ▪ Political structure ▪ Attitudes ▪ Values *Cited from Turner et al., 1993*	NA	▪ Economic incentives developed by governments are the key cause of deforestation. ▪ Interdisciplinary studies of land-use and climate change effects are necessary. ▪ Land-use changes are having major ecological repercussions at a variety of biological scales.
Dirzo and Raven, 2003 **Theme: Biodiversity**	No definitions provided. Terms 'proximal drivers' and 'ultimate drivers' used.	IPAT is mentioned but not applied to drivers.	Proximal drivers affecting mammalian species, threatened birds and plants: ▪ Habitat loss/degradation caused by: - Agricultural activities		Global level	▪ Biodiversity loss is the only irreversible global environmental change. ▪ Biological extinction is rooted in social,

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			(crop and livestock farming and plantations) - Extraction activities (mining, fishing, logging and harvesting) - Infrastructure development (human settlements, industry, roads, dams and power lines) ▪ Direct exploitation ▪ Introduction of alien invasive species of plants and animals *In order of importance*			economic, and political drivers.
Evans et al., 2005 **Theme: Freshwater ecosystems**	No definitions provided. Term 'drivers' used.	No framework	Drivers of change in dissolved organic carbon (DOC): ▪ Recovery from acidification (e.g. soils buffering acid impact) ▪ Temperature change ▪ Hydrological changes (e.g. increased flow, rainfall & runoff) ▪ Land uses ▪ In-lake and in-stream removal ▪ Nitrogen enrichment ▪ Atmospheric CO2 enrichment		United Kingdom, 22 water sources (11 lakes, 11 streams)	▪ There is evidence that DOC concentrations have increased during the last two decades in the United Kingdom 22 upland surface waters. ▪ There is a need to apply models to predict future response of terrestrial carbon stores to changes in climatic and/or deposition drivers, and to simulate the chemical and biological impacts of these changes on aquatic ecosystems.
Geist and Lambin, 2001	**Proximate causes:** (Near-final or final) Human activities that	IPAT is mentioned and critiqued.	Agricultural expansion ▪ Permanent cultivation ▪ Shifting cultivation	Demographic ▪ Natural increment ▪ Migration	Sub-national	▪ The leading proximate cause of tropical deforestation is the

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Theme: Forests	directly affect environment (cited by Turner et al.) and appear to operate at the local level **Underlying driving forces (or social processes):** Fundamental forces that underpin the more obvious or proximate causes of tropical deforestation. They may operate directly at the local level or indirectly at the national and global level		▪ Cattle ranching ▪ Colonization Wood extraction ▪ Commercial ▪ Fuelwood ▪ Polewood ▪ Charcoal production Infrastructure extension ▪ Transport ▪ Markets ▪ Settlements ▪ Public services ▪ Private company Other factors ▪ Pre-disposing environmental factors ▪ Biophysical drivers ▪ Social trigger events (e.g. war, revolution, social disorder)	▪ Population density ▪ Population distribution ▪ Life cycle features Economic ▪ Market growth and commercialization ▪ Economic structures ▪ Urbanization and industrialization ▪ Special variables Technological ▪ Agro-technical change ▪ Applications in wood sector ▪ Agricultural production factors Policy and institutional factors ▪ Formal policies ▪ Policy climate ▪ Property rights Cultural factors ▪ Public attitudes, values and beliefs ▪ Individual and household behaviour		expansion of cropped land and pasture. ▪ The most prevalent underlying causes are economic factors (single and multi-factorial driver combinations), followed by policy and institutional, technological, socio-political / cultural and demographic factors.
Grainger, 1993 **Theme: Forests**	No definitions provided. Terms 'underlying causes' and 'driving forces' interchangeably.	No framework	Immediate causes/drivers of tropical deforestation: ▪ Shifting agriculture (e.g. short-rotation shifting cultivation) ▪ Permanent agriculture (e.g. fish farming, cattle ranching, and staple crop cultivation)	Underlying causes/drivers of tropical deforestation: Socio-economic factors: ▪ Population growth ▪ Economic development ▪ Poverty Physical and environmental factors: ▪ Distribution of forests	Local, national and global scale	▪ Economic development promotes deforestation and also can slow it down and control it. ▪ Social and economic polities should be developed parallel to forest and agricultural policies.

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Author, date, and theme	**Definition/ terminology**	**Framework / scenario applied**	**Direct drivers**	**Indirect drivers**	**Spatial and temporal scale**	**Findings**
			▪ Mining ▪ Hydro-electric schemes ▪ Cultivation of illegal narcotics	▪ Proximity of rivers ▪ Proximity of roads ▪ Distance from urban centre ▪ Topography ▪ Soil fertility Government policies*: ▪ Agriculture policies ▪ Forestry policies ▪ Other policies ** Government policies affect land use changes both directly and indirectly.*		▪ Lack of sustainability of forest management is due to the failure of government forest policies and institutions. ▪ Great uncertainty exists regarding the annual deforestation rates and size.
Houghton, 1994 **Themes: Land and Forests**	No definitions provided. Terms 'agents' and 'forces' used.	No framework	Agents in deforestation: ▪ Conversion to cropland ▪ Conversion to pastures ▪ Conversion to grazing land ▪ Selective logging	Agents in land use change: ▪ Global economy ▪ International trade ▪ Urban growth Global forces responsible for change: ▪ Economic development ▪ Population growth ▪ Environmental degradation ▪ Agriculture expansion for exports Major factors determining agricultural expansion: ▪ National debt ▪ International trade Cause of tropical deforestation: ▪ Distribution of wealth between developed and		▪ Rates of land use change are often parallel with rates of population growth. ▪ Rates of land use change often diminish at local levels with increased economic development. ▪ Approximately a third of the land surface is being used as croplands or pastures. ▪ National debt and international trade are major factors in determining agricultural expansion.

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				developing nations		
Kates et al., 1990 **Theme: Biodiversity**	**Driving forces:** Actions that change nature from its conditions independent of humankind **Behaviour:** The underlying rationales, both conditions and choices, for the actions that give rise to driving and mitigating forces **Mitigating forces:** Countervailing influences that operate to reduce or alter the driving forces of their impacts Term 'components' used.	No framework		Components of driving forces: ▪ Population ▪ Technological capacity ▪ Socio-cultural organization Components of mitigating forces: ▪ Authoritative regulation ▪ Market adjustment ▪ Informal social regulation	Global scale	▪ Changes in the 3 driving forces will affect demand and supply of resources, the distribution and access to the supply, which will result in the transformation of the biosphere. ▪ To understand these forces, it is important to also place these forces within the context of human and social rationales of action.
Kennish, 2002 **Theme: Coastal and marine ecosystems**	No definitions provided. Terms 'anthropogenic impacts' and 'anthropogenic activities' interchangeably used. When making reference to the potential state in the future, the term 'anthropogenic threats' is used.	No framework	▪ Pollution inputs: - Nutrient enrichment - Organic carbon loading - Oil spills - Toxic chemicals - Debris/litter ▪ Habitat loss and alteration ▪ Fisheries exploitation ▪ Freshwater diversion ▪ Introduced species ▪ Shoreline development & dredging	▪ Accelerated population growth ▪ Development (controlled and uncontrolled) in coastal regions ▪ Increasing urbanization and industrialization ▪ Tourism	Global scale of estuaries Current situation and future state in 2025	▪ Estuaries rank among the most heavily impacted aquatic systems on Earth. ▪ Pollution and habitat degradation due to human activities have created serious environmental problems in these areas. ▪ One of the main human

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			▪ Habitat restoration ▪ Sea level rise			activities is the continually expanding coastal population, expected to reach six billion people by 2025. ▪ Data gaps exist on human impacts on estuaries. ▪ Similar anthropogenic problems affect estuaries in both developed and developing countries. ▪ A global approach to protecting and managing the coastal zone is required. The UN convention on Law of the Sea (1994) is considered the beginning step.
Klug and Cottingham, 2001 **Theme: Freshwater ecosystems**	**Environmental drivers:** Exogenous or endogenous variables that cause measurable changes in properties of a community or ecosystem.	No framework	Two important environmental drivers in aquatic systems: ▪ Inorganic nutrients (e.g. nitrogen) ▪ Coloured dissolved organic matter		Regional study – lake in Michigan, USA	▪ The effects of multiple environmental drivers cannot be predicted by simply combining the effects of single environmental drivers. ▪ Research regarding direct and indirect effects of environmental drivers should include the anticipation of when the interactions among drivers are likely to occur.

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Kummer and Turner II, 1994 **Theme: Forests**	**Systematic change:** Biogeochemical flows that operate globally (e.g., trace gases) **Cumulative change:** Changes on the surface of the earth, independent of geochemical flows. Only a global concern if changes reach a large enough magnitude or spatial scale (e.g. loss of biodiversity) **Underlying human (socio-economic) and biophysical drivers:** Direct the course of land use Terms 'drivers', 'forces' and 'proximate causes' used.	No framework	Proximate causes of deforestation in Philippines: ▪ Large-scale logging ▪ Agricultural expansion	Underlying causes of deforestation in Philippines: ▪ Corrupt political structures ▪ Logging was driven by the international market demand for tropical woods *These processes of deforestation were followed by building roads for logging and non logging purposes and population growth.*	Philippines 1970-1980	▪ Population growth was not a major driving force of deforestation –even though, population growth in region had been significant. Possibly, population growth has had an impact on deforestation but in a complex and indirect way that is not detectable through the applied model. ▪ In Southeast Asian countries, deforestation occurs due to government policy. ▪ Little evidence to support that deforestation is linked to local and national increases in per capital consumption.
Lake and Bond, 2007 **Theme: Freshwater ecosystems**	No definitions provided. Term 'drivers' used.	Three scenarios: Business as usual Economic growth Ecological sustainability	▪ Irrigated agriculture (accounts for 75% of water consumption) ▪ Industrial uses (power generation, mining, cooling, etc.) ▪ Farm dams ▪ Land clearing ▪ Grazing ▪ Catchment alterations ▪ Sediment and nutrient inputs	▪ Lack of planning in water resource development ▪ European immigrants (200 years ago) ▪ Economic growth ▪ Production of cotton	Australia 2030-2050	▪ Climate change and salinity are two forces likely to increase in strength and spatial scale in the next 30–50 years. ▪ In all scenarios, there is a strong growth in water use and reuse technologies to increase the efficiency with which water is used.

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			▪ Salinisation ▪ Climate change ▪ Toxic pollutants ▪ Invasive species			▪ Significant changes in water resource management are beginning to occur, but too early to assess impacts.
Lambin et al., 2003 **Theme: Land**	**Proximate (or direct) causes of land use change:** Human activities or immediate actions that originate from intended land use and directly affect land cover (cited by Ojima). Generally operate at local level. **Underlying (or indirect or root) causes:** Fundamental forces that underpin the more proximate causes of land cover change and operate more diffusely.	No framework applied but the following frameworks discussed: ▪ Agent-based perspective ▪ Systems perspective ▪ Narrative perspective	▪ Agricultural expansion ▪ Irrigation ▪ Nitrogen and phosphorus fertilizers ▪ Climatic variations ▪ Natural disasters (e.g. floods, droughts)	Sectoral causes of land use change: ▪ Natural variability ▪ Economic and technological factors ▪ Demographic factors ▪ Cultural factors ▪ Globalization* ** Globalization is a process that underlies the above causes and has a direct and indirect impact on the above causes.* Fundamental high level causes of land use change**:** ▪ Resource scarcity ▪ Changing opportunities created by markets ▪ Outside policy intervention ▪ Loss of adaptive capacity and increased vulnerability ▪ Changes in social organization, resource access and in attitudes		▪ Need to understand how people make land use decisions in order to identify the causes of land use change. ▪ An integrative framework encompassing a unified theory on the causes and pathways of land use changes is required to research this topic further. ▪ Land use change is the sum of many small, local-scale changes in land allocation.
McNeely et al., 1995	**Indirect causes/ mechanisms** (of biodiversity loss):	No framework	▪ Habitat loss and fragmentation ▪ Invasion by introduced	▪ Human social organization ▪ Human population growth		▪ Biotic impoverishment is an almost inevitable

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Theme: Biodiversity	Factors that have led to the expanding ecological niche of humans Terms 'indirect mechanisms' and 'direct mechanisms' used.		species (negative and positive effects) ▪ Over-exploitation of living resources ▪ Pollution of soil, water and atmosphere ▪ Domestication and selection ▪ Global climate change ▪ Expansion of agriculture, forestry and aquaculture	▪ Natural resource consumption patterns ▪ Global trade ▪ Economic systems and policies that fail to value the environment ▪ Inequity in the ownership, management, and flow of benefits from both the use and conversation of biological resources ▪ Changes in attitudes towards nature		consequence of the ways in which the human species has used and misused the environment. In the course of its rise to dominance. ▪ Biodiversity loss in recent historical times is due to human activities, primarily land use. ▪ No agreement exists on the level at which there is adequate explanation achieved for underlying causes.
Meyer and Turner II, 1992 **Theme: Land**	**Proximate sources of change**: Human actions that directly alter land cover, with further environmental consequences that may ultimately feed back to affect land use **Driving forces:** Human goals that shape the proximate sources (human activities). Natural drivers not mentioned.	IPAT is mentioned and criticized.	▪ Land use/land cover	▪ Population growth ▪ Technological change ▪ Socio-economic organization ▪ Level of economic development ▪ Culture	Global scale	▪ Research on human driving forces at global scale is in disarray ▪ Driving forces of change may vary with the type of change involved; forces that drive some changes may lesson others. ▪ The same kind of land-cover change can have different proximate sources in different area even within particular world regions ▪ No agreement exists regarding underlying causes on the level at which adequate explanation is achieved.

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						▪ Limited confidence in literature review and assessments on driving forces, therefore more attention should be given to driving forces. ▪ The broad patterns of land use/cover changes are known with some confidence. ▪ Avenues of dealing with driving forces: 1. Using a wiring diagram to outline the structure of interaction between society and land; 2. Seek a middle scale between global and local at which to address driving force-change relationships;
Mikkelson et al., 2007 **Theme: Biodiversity**	No definitions provided. Use of terms 'proximate causes' and 'biophysical drivers' interchangeably.	Gini ratio	▪ Habitat destruction ▪ Climate change ▪ Biotic homogenization ▪ Resource extraction ▪ Pollution		National scale and regional (US states) scale	▪ Found striking relationships between income inequality and biodiversity loss. ▪ Societies with more unequal distributions of income experienced greater losses of biodiversity. ▪ Found that the overall size of an economy is not the primary driver of environmental impacts. ▪ Socio-economic forces behind the direct drivers

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						are poorly known
Nakicenovic et al., 2000 **Theme: Atmosphere**	No definitions provided Term 'driving forces' used Natural drivers not mentioned	IPAT identity Kaya identity	▪ Greenhouse gases	Driving forces of past and future anthropogenic greenhouse gas: ▪ Population ▪ Socioeconomic development processes (including technological change) ▪ Energy resources and technology ▪ Agriculture, forestry and land use change	Global and regional 1990, 2020, 2050, 2100	▪ Alternative combinations of driving forces can lead to similar levels and structure of energy and land-use patterns, as illustrated by different scenarios and groups.
Nelson et al., 2005 **Theme: Biodiversity**	**Driver**: any natural or human-induced factor that directly or indirectly causes a change in an ecosystem **Direct driver**: physical, biological, or chemical processes that tend to directly influence changes in ecosystem goods and services **Indirect driver**: operates more diffusely than direct drivers by altering one or more direct drivers *MA definition*	MA (Millennium Assessment) conceptual framework	▪ Climate variability and change ▪ Plant nutrient use ▪ Land conversion ▪ Invasive species ▪ Diseases ▪ Tourism* ▪ War ** Tourism is often seen as a positive direct driver of ecosystem change contributing to income generation and reduction in pressures.*	Demographic ▪ Population ▪ Fertility ▪ Mortality ▪ Migration Economic ▪ Consumption ▪ Production ▪ Globalization ▪ Economic growth ▪ Tourism Socio-political ▪ Education ▪ Human capital ▪ Research investments ▪ Extent of international cooperation ▪ Lifestyle choices affecting energy demand Cultural & religious Science & technology War	Global level, with some references to regional impacts	▪ The rate of conversion of inputs to economic outputs is an important determinant of the impact on ecosystems. ▪ The rate of change in scientific and technology knowledge is affected by decision makers. ▪ "No single conceptual framework exists that captures the broad range of case study evidence." (Lambin, 2001).

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Nelson et al., 2001 **Themes: Land**	No definitions provided.	Spatial econometric technique	▪ Land use	General land use determinants: ▪ Geophysical characteristics ▪ Socio-economic characteristics ▪ Technologies, combined with first two Land use protection determinants for Darien: ▪ Property rights ▪ Cultural factors	Darien province, Panama 1987-1997	▪ Legal protection of the national park seems to have made little difference to the land use within the park. ▪ Cultural land use practices combined with property rights influence land uses. ▪ A significant loss of forest would have happened if property rights were removed. ▪ Property rights do exert a significant impact on land use and forest cover in some parts of Darien, but the causality is not universal. It is location dependent and may also be correlated to cultural factors.
Olson et al., 2004 (a) **Themes: Land**	No definitions provided. Terms 'proximate drivers', 'underlying/ root causes', 'proximate causes', 'drivers' and 'forces' used.	Political Ecology Framework	▪ Land use change	**Driving forces of land use changes in East Africa:** ▪ Government policy, laws and regulations ▪ Economic factors ▪ Population growth and migration ▪ Changes in land tenure arrangements ▪ Market access and infrastructure development ▪ Environmental conditions	East Africa Landscape to broader scale 1950-to present	▪ Government policy, related laws and regulations are considered one of the least discussed drivers of land use change. ▪ In East Africa, governance has had significant impact on land use changes. ▪ Very often, research is focused on population

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				Underlying driving forces: ▪ Policies and government ▪ Economic change ▪ Regional characteristics ▪ Individual/household characteristics		growth, environmental and economic factors, without examining the role of past and present policies. ▪ There should be flexibility in future options for livelihood systems since there is still much uncertainty from systems dynamics.
Olson et al., 2004 (b) **Theme: Land**	No definitions provided. Terms 'proximate drivers', 'underlying/root causes', 'proximate causes', 'drivers' and 'forces' used	DPSIR is discussed but not applied. Political Ecology Framework	▪ Land use change	Processes affecting land use linkages to biodiversity and land degradation: ▪ Globalization ▪ National policies of land tenure and access to land ▪ Civil strife and insecurity ▪ Income diversification and urbanization ▪ Gender roles and labour allocation ▪ Differential poverty and wealth Root causes of land use change are based on: ▪ Changing rural economy ▪ Demographic trends ▪ Infrastructure development ▪ Polices and programs of land distribution, land tenure and protected areas ▪ Political situation ▪ Social factors	NA	▪ Land use degradation is the result of human factors combined with natural factors. ▪ No universal theory that identifies and conceptualizes land use changes exists. ▪ A multi-scale approach is mandatory in order to thoroughly understand trends and their causes.

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				▪ Climatic/hydrological factors ▪ Biological factors (e.g. disease)		
Redman, 1999 **Theme: Urban areas**	No definitions provided.	No framework		▪ Population doubled ▪ Local economy ▪ Neighbourhood age	Phoenix urban area, USA	▪ Practical approaches for investigations include: demographic patterns, economic systems, power hierarchies, land use and management, and designed environment.
Rosenzweig and Casassa, 2007 **Theme: Atmosphere**	**Non-climatic drivers:** Influence systems directly and indirectly through their effects on climate variables such as albedo. Socio-economic processes can affect multiple systems. These drivers operate independently or in association with one another (Lepers et al., 2004)	Scenarios	Non-climatic drivers: ▪ Land-use change ▪ Land cover modification ▪ Pollution ▪ Invasive species ▪ Over-exploitation of resources ▪ Geological processes Climatic drivers: ▪ Flooding ▪ Drought ▪ Wildfire ▪ Insects ▪ Ocean acidification	Socio-economic process that drive land use change: ▪ Population growth ▪ Economic development ▪ Trade and migration Non-climatic drivers: ▪ Technological change		▪ Technological change and regional land use policy in some scenarios are shown as most important drivers. ▪ Little evidence exists about the effects of climate change on human health. ▪ In mountainous regions, climate change is main driver of species composition, but grazing, logging and fuelwood can also be of considerable relevance, depending where.
Sala et al., 2000 **Theme: Biodiversity**	No definitions provided. Term 'drivers of biodiversity change' used.	Business as usual scenarios	Five most important drivers at the global scale: ▪ Changes in land use ▪ Atmospheric CO_2 concentration ▪ Nitrogen deposition and acid rain		Global scale, in 10 terrestrial biomes and freshwater ecosystems	▪ Land use change is the most severe driver of changes in biodiversity at the global level. ▪ Mediterranean and grassland ecosystems

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			▪ Climate ▪ Biotic exchanges (deliberate and accidental)		Time scale: up till 2100	will be most sensitive to global changes if it is assumed that these changes occur without interaction among the drivers. ▪ If biodiversity will be determined by the driver that has the greatest impact on the relevant biome, then: - Land use change will substantially affect tropical and southern temperate forests and; - Climate change will substantially affect arctic ecosystems. ▪ Mediterranean and grassland ecosystems will experience substantial changes if synergistic interaction occurs amongst all drivers.
Seto and Kaufmann, 2003 **Theme: Urban areas**	No definitions provided. Term 'drivers of urbanization' used.	Aspatial models used to quantify annual rates of land-use change and socio-economic data to determine what are the mechanisms that drive urbanization in Pearl River Delta	Drivers of urbanization in Pearl River Delta, China: ▪ Increase in motorized transport ▪ Increase in air, water and noise pollution ▪ Increase in energy consumption ▪ Loss of agricultural land ▪ Reduction in biodiversity	Indirect drivers of agricultural land converted to urban land in Pearl River Delta, China: ▪ Economic growth rapidly developed due to decentralized policies and market-oriented reforms as of 1979 ▪ Designation as Open	1988-1996 Pearl River Delta, China	▪ Urban growth is linked to foreign direct investment. ▪ The ratio of agricultural land productivity and industrial land productivity influence the conversion of natural ecosystems and

Table A: Research overview of drivers of environmental change

Author, date, and theme	Definition/ terminology	Framework / scenario applied	Direct drivers	Indirect drivers	Spatial and temporal scale	Findings
				Economic Region in 1988, providing region with special tax and trade status ▪ Transfer of land use rights, effective as of 1988 ▪ Investment in capital construction per capita ▪ Agricultural labour productivity ▪ Income ▪ Migration ▪ Population growth		agricultural land. ▪ Urban land use conversion appears to linked to large-scale investments in industrial development as opposed to local land use owners.
Spangenberg, 2007 **Themes: Biodiversity**	No definitions provided. 'Driving forces' and 'drivers' used synonymously and the latter is used as short for the former. Term 'anthropogenic pressures' used.	No framework	Pressures influencing ecosystems: ▪ Human overexploitation (logging, hunting, gathering, farming, grazing) ▪ Disturbed hydrological regimes from water logging, reduction of forest cover and changed precipitation patterns ▪ Climate change ▪ Pollution (acidification, eutrophication, accumulating chemicals and long-range air pollutants) ▪ Habitat fragmentation ▪ Introduction of foreign species ▪ Ecotoxics ▪ Genetic pollution from	Physical driving forces behind biodiversity loss in Europe: ▪ Energy consumption ▪ Land use intensity ▪ Land use planning ▪ Material flows ▪ Environmental chemicals ▪ Dissipative chemical use ▪ Chemicals production ▪ Consumption and waste generation ▪ Global trade ▪ GMO[20] production, trade and release ▪ Lack of regulation and monitoring Secondary drivers: Political driving forces behind biodiversity loss in Europe: ▪ European policies, such as the Common Agricultural	Europe	▪ Interventions for biodiversity conservation should be multi-faceted, should systematically cover a broad range of policy domains and should systematically combine legal, planning, economic and informational instruments.

[20] GMO: Genetically Modified Organisms

Table A: Research overview of drivers of environmental change

Author, date, and theme	Definition/ terminology	Framework / scenario applied	Direct drivers	Indirect drivers	Spatial and temporal scale	Findings
			deliberate releases of genetically modified organisms	Policy (CAP) and the Structural, Regional and Cohesion Funds, and legislations ▪ Infrastructure construction for the Trans European Network (TEN)		
Tilman et al., 2001 **Theme: Land**	No definitions provided. Terms 'drivers' and 'demand' used.	Univariate and multiple regressions	▪ Agricultural expansion	Two assumed greatest drivers of global environmental change: ▪ Population size ▪ Per capita consumption Driver of increase in land conversion to agriculture: ▪ Food demand by wealthier and growing population	Global scale 2020 and 2050	▪ Demand for agricultural products may be the major driver of future non-climatic global change. ▪ If trends continue, there will be an increase in land conversion to agricultural use, pesticide use and irrigated areas by 2050 that will impose significant impacts on ecosystems. ▪ Change in diets could reduce food demand. ▪ Dissemination of existing knowledge – could reduce environmental impacts of agriculture.
UNEP-GEO, 2002 **Themes: Forest,**	No definitions provided Terms 'driving force' 'drivers' ,'root causes' and 'direct cause' used interchangeably	No framework	Direct causes of forest clearance and degradation: ▪ Agricultural land expansion ▪ Overharvesting of industrial wood,	Driving forces for land resources: ▪ Increasing food production (main) ▪ Population growth	Global scale 1972-2002	▪ Land conversion is most intensive in tropical forests and less intensive in temperate, boreal and arctic regions.

Table A: Research overview of drivers of environmental change

Author, date, and theme	Definition/ terminology	Framework / scenario applied	Direct drivers	Indirect drivers	Spatial and temporal scale	Findings
Biodiversity, Coastal and marine ecosystems, and Urban areas.			fuelwood, and other forest products ▪ Overgrazing ▪ Natural factors such as insect pests, diseases, fire, and extreme climatic events Direct causes of biodiversity loss: ▪ Land conversion ▪ Climate change ▪ Pollution ▪ Unsustainable harvesting of natural resources ▪ Introduction of exotic species Root causes of marine and coastal degradation: ▪ Increasing urbanization ▪ Industrialization ▪ Tourism in coastal areas ▪ Sewage Root causes of environmental degradation due to urbanization: ▪ Resource consumption ▪ Waste discharges ▪ Inadequate waste collection and management systems	Underlying drivers of forest clearance and degradation: ▪ Poverty ▪ Population growth ▪ Markets and trade in forest products ▪ Macroeconomic policies Contributory factors to biodiversity loss: ▪ Human population growth together with: ▪ Unsustainable patterns of consumption ▪ Increasing production of waste ▪ Urban development and international conflicts Driving forces of marine and coastal degradation: ▪ Population Driving forces of environmental degradation due to urbanization: ▪ Population ▪ Consumption patterns ▪ Travel behaviour ▪ Urban economic activities ▪ Poverty (major cause) ▪ Poor management, poor planning and absence of coherent urban policies		▪ Major changes have occurred in human and environmental conditions over the past 30 years. ▪ The natural environment has been heavily used to meet the needs of the increasing population.

Table A: Research overview of drivers of environmental change

Author, date, and theme	Definition/ terminology	Framework / scenario applied	Direct drivers	Indirect drivers	Spatial and temporal scale	Findings
van Vuuren and Smeets, 2000 **Themes: Land and Atmosphere**	No definitions provided. Term 'driving forces' used.	Ecological footprint concept	Main direct drivers of land-use in the Netherlands: ▪ Food production ▪ Wood production Direct drivers of land-use in the Netherlands, Benin, Bhutan and Costa Rica: ▪ Wood consumption ▪ Animal products	Indirect driver of land use in Costa Rica: ▪ Economy: exports of fruits and coffee Indirect driver of land use in Bhutan: ▪ Environmental: Lack of arable land therefore, limited potential for agricultural expansion Indirect drivers of changes in total real net land use for agricultural products: ▪ Population increase ▪ Changes in consumption per capita ▪ Changes in consumption pattern ▪ Increase in productivity (crop yields) Indirect drivers of carbon dioxide emissions in the four countries: ▪ Population growth ▪ Change in activities (measured by GDP) ▪ Carbon intensity (carbon dioxide emissions per unit of GDP) – a function of energy efficiency, structural changes in the economy and type of fuel used.	National levels: Netherlands, Benin, Bhutan and Costa Rica 1980-1994	▪ Wood consumption used in four countries used for different purposes: in NL –wood is used as industrial round wood while in Benin it is used for fuel. ▪ High levels of agricultural productivity were linked to countries with high levels of consumption.

Table A: Research overview of drivers of environmental change

Author, date, and theme	Definition/ terminology	Framework / scenario applied	Direct drivers	Indirect drivers	Spatial and temporal scale	Findings
Vasconcelos et al., 2007 **Theme: Coastal and marine ecosystems**	No definitions provided. Term 'anthropogenic pressures' used.	Multi-metric index / Detrended Component Analysis / Principal Component Analysis Ecological conceptual model (adaptation of DPSIR framework of EEA)	▪ Excessive loading of nutrients, organic matter and contaminants ▪ Chemical contaminants (e.g., trace metals, hydrocarbons and synthetic organ compounds) ▪ Habitat loss ▪ Damming of freshwater flows ▪ Removal of invertebrates or fish ▪ High fish mortalities ▪ Agricultural, industrial and engineering projects ▪ Domestic and industrial discharges ▪ Port activities ▪ Polluted waters and run off ▪ Dredging ▪ Genetic introduction of exotic species	▪ Rapid population growth ▪ Uncontrolled development in coastal regions ▪ Environmental management	Country level (Portugal)	▪ There is no evident direct link between the anthropogenic pressures assessed and nursery fish species. ▪ Portuguese estuaries are poorly studied.
Verbist et al., 2005 **Theme: Land**	**Proximate causes of deforestation:** Human activities at the local level that originate from intended land use and that have a direct impact on forest cover. **Underlying driving factors of deforestation:** Fundamental social	A framework established by Geist and Lambin (2002)	▪ Agricultural expansion over last 30 years: coffee gardens ▪ Wood extraction ▪ Trans-Sumatra highway connection in 1950s ▪ Environmental factors: suitable soils for growing coffee, ample and regular rainfall, and suitable altitude	▪ Socio-economic: Wood extraction was an important source of income until late 1970s ▪ Technology: The highway development caused a decrease in transportation costs and an increase in accessibility ▪ Political: Change in political government in 1998, which caused more	Sub-district in Sumberjaya (West Lampung Province)	▪ Deforestation is only the first phase of land use change. ▪ All the proximate and underlying causes listed by Geist and Lambin (2002) are present in this case study.

Table A: Research overview of drivers of environmental change

Author, date, and theme	Definition/ terminology	Framework / scenario applied	Direct drivers	Indirect drivers	Spatial and temporal scale	Findings
	processes that underpin the proximate causes and which either operated at the local level or have indirect impacts that are felt at the local level. *Definitions cited from Geist and Lambin (2002).*			land buyers. ▪ Economic: market coffee prices ▪ Demographic: Migration, specifically between 1978-1988 when the population doubled ▪ Political: Great ambiguity exists with land tenure and legislations		
Vinebrooke et al., 2004 **Theme: Freshwater ecosystems**	**Stressors**: An abiotic or biotic (e.g. introduction of an alien species) variable that exceeds its range of normal variation, and adversely affects individual physiology or population performance in a statistically significant way. Stressors can be natural and anthropogenic.	No framework	Stressors in terrestrial ecosystems: ▪ Increased eutrophication ▪ Salinisation ▪ Synthetic organic pollutants Stressors in northern freshwater ecosystems: ▪ Anthropogenic acidification ▪ Drought events ▪ Depletion of stratosphere ozone ▪ Exposure to DNA-damaging ultraviolet radiation		NA	▪ The sign and strength of correlations between stressor tolerances affect the response of biodiversity and ecosystem functioning to multiple stressors.
Walker et al., 2000 **Themes: Forests**	**Proximate causes of deforestation:** Altered, land management systems Terms 'proximate causes', 'driving forces' used 'household drivers' used.	No framework	Causes of deforestation: ▪ Pasture creation ▪ Cattle ranchers ▪ Labour force	Underlying causes of deforestation: ▪ Government incentive programs in Para, Mato Grosso and Rondonia ▪ Transportation costs ▪ Economic incentives, including current market conditions for beef	Amazonia	▪ Large and small producers are responsible for deforestation for cattle ranches. ▪ Deforestation is related to the availability of financial resources that enable labour

Table A: Research overview of drivers of environmental change

Author, date, and theme	Definition/ terminology	Framework / scenario applied	Direct drivers	Indirect drivers	Spatial and temporal scale	Findings
				production and profits		contracting. ▪ Policies aimed at reducing the rate of deforestation should be targeted at specific groups (e.g. small producers or large scale ranchers) and specifically at the cattle economy.
Xie at el., 2005 **Theme: Land**	No definitions provided. Term 'driving forces' used.	Regression analysis to identify and quantify the relationships between paddy field conversion and selected policy, demographic, and socio-economic factors.	▪ Land use conversion	Driving forces of arable land conversion: ▪ Government priority to promote socio-economic growth in 1990-1995 ▪ New policy directives, which was not very successful at protecting arable lands. Driving forces of paddy land conversion from 1990-1995: ▪ Total income of rural economy ▪ Gross domestic product value ▪ Urban construction ▪ Rural construction ▪ Transportation construction	Wuxian City, China 1990-1995	▪ Rapid economic growth led to rapid urban expansion and the affluent rural residents where consuming arable land for residences/ services ▪ In 1995-2000, the strict policies to control investment and urban expansion are noticeable. ▪ The improvement of productivity and machinery use in agriculture has resulted in a surplus of labours. Therefore, the population is rapidly moving from farms into the cities causing urban expansion and farm land loss.

Appendix II: Keywords and data sources

Key words

- Drivers[21] AND ecosystem[22] OR biodiversity
- Proximate causes AND ecosystem OR biodiversity
- Driving forces AND ecosystem OR biodiversity
- Stressors AND ecosystem OR biodiversity
- DPSIR framework

Data sources

- University of Edinburgh Library www.lib.ed.ac.uk/
- ScienceDirect: www.sciencedirect.com
- Highwire Press: //highwire.stanford.edu/
- Swetswise: //carlin.lib.ed.ac.uk:2065/eAccess/searchArticles.do
- Springerlink: www.springerlink.com/home/main.mpx
- Web of Knowledge / Science: //wok.mimas.ac.uk/
- Elsevier Science: www.elsevier.com/
- Blackwell Synergy: www.blackwell-synergy.com
- Millennium Ecosystem Assessment: www.millenniumassessment.org
- International Geosphere-Biosphere Programme: www.igbp.kva.se/
- Intergovernmental Panel on Climate Change: www.ipcc-wg2.org/

[21] Social AND/OR economic AND/OR environmental drivers
[22] E.g. Drivers and forests

Appendix III: Definitions for themes

Themes have been derived from the Millennium Ecosystem Assessment Report, specifically from Chapter one, MA Conceptual Frameworks
(Carpenters et al., 2005:31).

Theme	Definition
Land	Cultivated lands, scrublands, shrublands, grasslands, semi-desserts, and true desserts.
Forests	Lands dominated by trees, includes temporarily cut-over forests and plantations.
Biodiversity	Biodiversity is the variability among living organisms from all sources, including terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part. It includes diversity within and between species and diversity of ecosystems.
Freshwater ecosystems	Rivers, lakes, floodplains, reservoirs, and inland wetlands; includes inland saline system.
Coastal and marine ecosystems	Ocean and marine areas as well as the interface between ocean and land extending to a distance of 100 kilometres from shore. This includes coral reefs, inter-tidal zones, estuaries, coastal aquaculture, and seagrass communities.
Atmosphere	The mass of air encompassing the earth.
Urban areas	Built environments with a high human density.

Appendix IV: Abbreviations

Abbreviations	
CAP	Common Agricultural Policy
DPSIR	Drivers- Pressures -States-Impacts -Responses Framework
EEA	European Environmental Agency
EU	European Union
FAO	Food and Agricultural Organization of the United Nations
GBA	Global Biodiversity Assessment
GDP	Gross Domestic Product
GEO	Global Environment Outlook
GIWA	Global International Water Assessment
GMO	Genetically modified organism
GNP	Gross National Product
HDI	Human Development Index
IGBP	International Geosphere-Biosphere Programme
ISEW	Index of Sustainable Economic Welfare
LUCC	Land-Use/Cover Change
MA	Millennium Ecosystem Assessment
NUP	Stockholm National Park Urban Park
PPP	Purchasing Power Parity
RDA	Royal Djurgården Administration
UNEP	United Nations Environment Program
US	United States
WTO	World Trade Organization

Appendix V: Glossary

Term	Definition
Biodiversity	Biodiversity is the variability among living organisms from all sources, including terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are a part. It includes diversity within and between species and diversity of ecosystems (Carpenter et al., 2005:1:29).
Direct drivers	Direct drivers are the physical, biological or chemical processes that tend to directly influence changes in ecosystem goods and services (Nelson et al., 2005).
Drivers	Drivers are any natural or human-induced factors that directly or indirectly cause a change in an ecosystem (Nelson et al., 2005).
Ecosystem	An ecosystem is a dynamic complex of plant, animal, and microorganism communities and the nonliving environment interacting as a functional unit. (Carpenter et al., 2005:1:29).
Ecosystem services	Ecosystem services are the benefits people obtain from ecosystems. These include provisioning (e.g. food), regulating (e.g. biophysical processes), cultural (e.g. recreational), and supporting (e.g. nutrient cycling) (Carpenter et al., 2005:1:29).
Endogenous	Disturbances that are internal to a defined system (Stirling, 2007).
Exogenous	Disturbances that are external to a defined system (Stirling, 2007).
Indirect drivers	Indirect drivers are factors that operate more diffusely than direct drivers, often by altering one of the more direct drivers (Nelson et al., 2005).
Levels	Levels (e.g. micro, meso and macro) are the units of analysis that are located at the same position on a scale (Gibson et al., 2000).
Scales	Scale is the spatial, temporal, quantitative or analytic dimensions used by scientists to measure and study objects and processes (Gibson et al., 2000).
Sustainable development	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987).